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THERMAL FATIGUE AND OXIDATION DATA FOR ALLOY/BRAZE COMBINATIONS

by

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16 Abstract

Thermal fatigue and oxidation data were obtained for 62 brazed specimens of three iron-, three nickel-, and one cobalt-base alloy Fluidized bed thermal cycling was conducted over the range 740/25°C employing 10 cm long single-edge wedge specimens Immersion time was always 4 min in each bed Three types of test specimens were employed in the program (1) Group BR1 had brazed overlays on the specimen radius, (2) Group BR2 were butt brazed at midspan, and (3) Group BR3 specimens had a brazed foil overlay on the specimen radius Five of the eighteen braze overlay specimens generated fatigue cracks by 7000 cycles Thermal cracking of butt brazed specimens occurred exclusively through the butt braze Seven of the twenty-three butt brazed specimens survived 11,000 thermal cycles without cracking Only two of the twenty-one foil overlaid specimens exhibited cracking in 7000 cycles Blistering of the foil did occur for two alloys by 500 cycles Oxidation of the alloy/braze combination was limited at the maximum test temperature of 740°C

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FOREWORD

This report, "Thermal Fatigue and Oxidation Data for Alloy/Braze Combinations," summarizes the thermal fatigue and oxidation testing of brazed stainless steels and superalloys on Contract NAS3-18942. Work described herein was conducted during the period May 1975 through May 1977. All testing in this program was conducted using fluidized bed heating and cooling over the range 740°/25°C (1364°/77°F). Other thermal fatigue data generated in this facility have been reported in NASA CR-72738, CR-121211, CR-121212, CR-134775, and CR-135272.

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SUMMARY

This report describes the results of fatigue and oxidation testing of braze/alloy combinations. All testing was performed employing fluidized bed heating and cooling. Other thermal fatigue data generated in this facility have been reported in NASA CR-72738, CR-121211, CR-121212, CR-134775, and CR-135272.

Thermal fatigue and oxidation data were obtained for 62 brazed specimens of three iron-, three nickel-, and one cobalt-base alloy. Fluidized bed thermal cycling was conducted over the range 740/25°C employing 10 cm long single-edge wedge specimens. Immersion time was always 4 min in each bed. Three types of test specimens were employed in the program. Group BR1 had an overlay of braze on the specimen radius. Group BR2 were butt brazed at midspan. Group BR3 specimens had a foil (same as the substrate) brazed over the specimen radius.

Five of the eighteen braze overlay specimens--316 + AMI-100, 316 + 60 Alloy, Incoloy 800 + CM 52, Inconel 600 + CM 50, and Inconel 600 + Palniro 1--generated fatigue cracks in 7000 cycles.

Thermal cracking of butt brazed specimens occurred exclusively through the butt braze. Seven of the twenty-three butt brazed specimens--Incoloy 800 + CM 52, Inconel 600 + AMI-100, Inconel 600 + CM 50, HS 188 + AMI-100, HS 188 + J8400, René 41 + Palniro 1, and René 41 + AMI-100--survived 11,000 thermal cycles without cracking. Three of five specimens brazed with AMI-100 survived 11,000 cycles. Alloy/braze combinations 316 + Nioro, 316 + 60 Alloy, 316 + AMI-100, 347 + NB50, Incoloy 800 + AMI-100, and HS 188 + CM 52 developed cracks in 6-88 cycles. Cracking of the remaining butt brazed specimens occurred in 1250-3250 cycles.

Only two of the twenty-one foil overlaid specimens, 347 + NB50 and Hastelloy X + CM 50, exhibited cracking in 7000 cycles. Blistering of the foil did occur in 100-300 cycles for 316 substrates and in 500 cycles for Incoloy 800 + Palniro 1.

Oxidation of the alloy/braze combination was limited at the maximum test temperature of 740°C. The braze alloy overlay combination 316 + 60 Alloy did undergo higher weight loss, 1.2%, in 7000 cycles.

1. INTRODUCTION

This report, NASA CR-135299, on Contract NAS3-18942 contains thermal fatigue and oxidation data on 62 specimens of brazed stainless steel, nickel-, and cobalt-base alloys Three types of single-edge wedge test specimens were evaluated. Group BR1 consisted of 18 specimens with a braze overlay on the radiused section of the sample. The 23 Group BR2 specimens were butt brazed at midspan, and the 21 Group BR3 were fabricated by brazing a foil of the parent metal over the radiused edge. All brazed specimens were supplied by the NASA-Lewis Research Center.

Test specimens were cycled in a fluidized bed facility over the temperature range 740°/25°C (1364°/77°F) for periods of up to 11,000 cycles. Heating and cooling times were 240 sec each for a total cycle of 480 sec. Weight change, as well as thermal crack initiation and propagation, was obtained in the program.

Thermal fatigue data obtained previously in the IITRI fluidized bed facility on Contract NAS3-17787 have been reported in NASA CR-134775[1] and CR-135272.[2] Other data obtained on Contract NAS3-14311 are reported in NASA CR-72738,[3] CR-121211,[4] and CR-121212.[5] This effort comprises part of a general study of thermal fatigue being conducted by the NASA-Lewis Research Center. Further details of the study have been reported by Spera et al.,[6,7] Bizon, et al.,[8-10] and Howes.[11]

Any material exposed to repeated temperature transients is subject to tensile failure by thermal fatigue, sometimes also defined as thermal shock. The thermal fatigue degradation mechanism involves accumulation of damage during multiple thermal cycles. Thermal shock, on the other hand, generally involves failure in relatively few cycles. The difference generally lies in the tensile ductility of the material within the temperature range of the imposed thermal cycle. Ductile materials tend to fail by thermal fatigue, whereas brittle materials fracture by thermal shock.

Material properties, other than ductility, important in thermal fatigue are hot tensile strength, elastic modulus, thermal conductivity, and thermal expansion. Oxidation resistance apparently also plays a role in thermal fatigue. The interrelationship of material properties, the imposed thermal cycle, and component geometry defines the ability of a structure to resist thermal fatigue. However, the synergistic effects of these variables are quite complex and prediction of thermal fatigue behavior from basic properties is difficult. A major objective of the current NASA program is to develop and verify a viable statistical model for thermal fatigue by comparing experimental data with computer-derived predictions of thermal fatigue life.

Thermal fatigue data in this report were generated using a multiple retort fluidized bed test facility consisting of one heating bed and two cooling beds. Glenny and co-workers reported the first use of fluidized beds to study thermal fatigue.[12] Fluidized bed heating and cooling provides very rapid heat transfer for both portions of the thermal cycle. An additional advantage of the fluidized bed method is that it provides a ready means of exposing a number of samples under identical test conditions. In this program, up to 36 test specimens were exposed simultaneously.

The objective of the thermal fatigue test program was threefold:

1. Determine the number of imposed thermal cycles to initiation of the first transverse crack.

2. Obtain data on the rate of propagation of the three largest cracks.

3. Generate qualitative oxidation data for the various materials.

Thermal cycling of test specimens was generally continued until the three largest cracks reached a length of about 6 mm. This corresponds approximately to the width of the radiused section of the test specimen. In some cases, testing of specimens was continued in order to obtain oxidation data for specific alloys.

Testing of braze alloy overlay Group BR1 was generally intended to define the effects of the braze alloy on thermal fatigue behavior of the substrate alloy. Thermal cracks generated in the braze overlay on the radius could propagate into the substrate alloy. Thus, a potential existed for reduced, or increased, thermal fatigue resistance of the braze alloy-substrate composite compared to the substrate alloy. Enhancement of thermal fatigue resistance of the composite could occur if the braze alloy was more resistant than the substrate alloy.

Testing of butt brazed Group BR2 specimens in this program was intended to evaluate the thermal fatigue behavior of high-temperature brazes under tension. Butt brazing at midspan resulted in evaluation of the fatigue behavior of both the braze alloy and the braze-substrate interface. Thermal fatigue data in this report do not distinguish the mode of failure, i.e., cracking within the braze alloy and/or at the braze alloy-substrate interface. Metallographic examination to be conducted subsequently at the NASA-Lewis Research Center should define the mode of tensile failure.

Group BR3 (foil brazed) specimens were intended to generally evaluate the integrity of the brazed joint. Since thermal cycling results in tensile stresses at the radius on cooling,

poor interfacial bonding should have caused separation of the foil from the substrate. This was evidenced in the test program as blistering of the foil overlays.

2. MATERIALS AND TEST METHOD

2.1 Materials and Specimens

The seven substrate materials employed for braze application were 316 and 347 stainless steels, René 41, HS 188, Incoloy 800, Inconel 600, and Hastelloy X. Actual chemical compositions for these alloys are contained in Table 1, along with the nominal compositions of the braze alloys.

Tables 2, 3, and 4 represent summaries of the specimen dimensions and identification of the three test groups, BR1, BR2, and BR3, respectively. Group BR1 consisted of 18 specimens of six alloys (excluding 347) with the braze alloys overlaid on the radiused section. The 23 specimens for Group BR2 were fabricated by butt brazing single-edge wedge test specimens at midspan. Finally, 21 Group BR3 specimens were fabricated by brazing a foil of the substrate alloy over the radiused area of the test specimens.

All test specimens were supplied by the NASA-Lewis Research Center. The butt brazed BR2 specimens were examined by X-ray inspection at NASA to insure sound brazed joints. Measurement of the wedge radius was conducted at IITRI.

2.2 Test Method

Thermal fatigue testing at 740°/25°C (1364°/77°F) was conducted in the IITRI fluidized bed facility shown schematically in Figure 1. This facility consists of one heating bed and two cooling beds permitting simultaneous testing of up to 36 specimens in two groups of 18 samples. Transfer between beds was obtained by an air cylinder actuated mechanism in about 5 sec. Heating was accomplished with SiC heating elements, and cooling of the cold beds was obtained by water-cooled heat exchangers. The heat transfer media employed in both heating and cooling beds was 28-48 mesh alumina.

Test specimens employed in this program were simulated leading edge, single-edge wedge specimens. The test specimen and the holding fixture capable of supporting 18 specimens are shown in Figure 2. During testing, the wedge areas of adjacent specimens were reversed in the fixture to provide maximum heat transfer to the specimen radius and temperature uniformity. This specimen arrangement was determined to be optimum by thermocouple calibrations of single-edge wedge specimens on Contract NAS3-17787.

All fatigue testing was conducted over the temperature range 740°/25°C. Heating and cooling times were 240 sec each for a total cycle of 480 sec. This test cycle is also being employed for evaluation of the substrate alloys on Contract NAS3-17787.

Specimens were removed at nominally 25, 50, 100, 200, 300, 500, 700, and 1000 cycles, and each 500 cycles above 1000 cycles, for gravimetric analysis and crack measurements. In addition, Group BR2 specimens were also examined at 12, 37, 75, 150, and 400 cycles. Cycles to crack initiation were determined to be the mean of the last inspection period without cracks and the first inspection period that cracks were visible. For example, if no cracks were visible at 500 cycles, but were detected at 700 cycles, the exposure to first crack was considered to be 600 cycles. Crack lengths were determined by microscopic measurements at 30X.

Testing of specimens was nominally conducted through 7000 cycles. However, seven of the butt brazed Group BR2 specimens that survived 7000 cycles without cracking were exposed for 11,000 cycles along with the Group BR3 specimens. These specimens were originally cycled with the Group BR1 samples.

3. EXPERIMENTAL RESULTS

3.1 Oxidation

Tables 5, 6, and 7 contain weight change data for Groups BR1, BR2, and BR3, respectively. Weight change data in Tables 5 to 7 are calculated as percent weight change since oxidation was not uniform over the test specimens. The radiused area of the test specimen was subjected to the maximum temperatures for longer periods than the thicker section of the specimen. Accordingly, oxidation of the wedge area was generally greater than the remaining areas of the specimen. In the case of Group BR1, weight change of the braze alloy overlay on the radius probably contributed most of the weight change. At the relatively low maximum temperature of 740°C (1364°F), little oxidation occurred for most parent alloys.

Weight change data in Table 5 indicate weight losses of 0.09 to 0.13% (0.1 to 0.2 gm) for Hastelloy X, René 41, and HS 188 in 7000 cycles, independent of the braze overlay. Higher weight losses, 0.27 to 0.51% (0.4 to 0.8 gm), were determined for 316, Incoloy 800, and Inconel 600, except for the 316 + 60 Alloy specimen 316-2. This specimen lost 1.2% (1.3 gm) weight in 7000 cycles with a high weight loss of 0.4% after 100 cycles. Unfortunately, no other specimen had a 60 Alloy overlay, so that the behavior of this braze alloy was not correlated.

Ranking of Group BR1 alloy/braze combinations is only qualitative since both substrate and braze alloys contributed to the weight change. Based on the substrate alloys, the following increasing order of oxidation resistance was obtained: 316, Incoloy 800, Inconel 600, Hastelloy X, HS 188, and René 41. For the braze alloys, only the unusually high weight loss for the 60 Alloy can be identified from the data.

Weight change data for Group BR2 specimens in Table 6 is somewhat limited because several specimens fractured through the brazed joint and could not be supported in the test fixture. Data exist for seven specimens through 11,000 cycles, as described previously. As a result of the variable exposures, complete ranking of the alloys in terms of oxidation resistance was not possible. However, for the specimens that survived 11,000 cycles, ranking in order of decreasing weight loss was Incoloy 800, Inconel 600, René 41, and HS 188.

Weight change data through 7000 cycles for the 21 Group BR3 specimens are contained in Table 7. As for Group BR1 and BR2, weight loss was relatively low, 0.1 to 0.3% after 7000 cycles. Because of blistering of the foil, 316 specimens were removed early in the exposure and only limited oxidation data were obtained. Other specimens, Inconel 600 + Palniro 1, Incoloy 800 + Palniro 1, and Incoloy 800 + CM 52, were substituted for 316 samples as they were removed from testing. Based on the 7000 cycle exposure, ranking of the alloys in order of decreasing weight loss was 347, Incoloy 800, Inconel 600, Hastelloy X, HS 188, and René 41. This is the same ranking observed for the Group BR1 specimens.

3.2 Thermal Fatigue

Table 8 is a summary of the cyclic exposure to first crack initiation for the 18 Group BR1 specimens. The alloys are generally listed in base alloy groupings in order of increasing resistance to thermal cracking. Only 5 of the samples, 316 + 60 alloy, 316 + AMI-100, Incoloy 800 + CM52, Inconel 600 + CM 50, and Inconel 600 + Palniro 1 exhibited transverse radius cracks prior to 7000 cycles. No cracks were observed after 7000 cycles on any alloy/braze combination with Hastelloy X, HS 188, and René 41 as the substrate alloy.

Fatigue data in Table 8 for 316 indicate that 316 specimens with 60 Alloy and AMI-100 generated cracks at 2750 and 3250 cycles, respectively. Alloy 316 + Nioro survived 7000 cycles without cracking. The combination Incoloy 800 + CM52 developed a crack at 2750 cycles, whereas Incoloy 800 + AMI-100 and Incoloy 800 + Palniro 1 did not develop cracks in 7000 cycles. Similarly, Inconel 600 + CM 50 and Inconel 600 + Palniro 1 indicated cracking in 4750 cycles, whereas Inconel 600 + AMI-100 survived 7000 cycles without cracks.

Table 9 summarizes the cracking behavior of the 23 butt brazed Group BR2 specimens. Both cycles to first crack and cycles to complete separation are included in the data. Thermal cracking for these specimens invariably occurred through the midspan brazed area. Only seven alloy/braze combinations survived the 7000 cycle exposure; these specimens also survived extended exposure of 4000 additional cycles without cracking. Alloy/braze combinations that survived 11,000 total cycles included Incoloy 800 + CM 52, Inconel 600 + AMI-100, Inconel 600 + CM 50, René 41 + Palniro 1, René 41 + AMI-100, HS 188 + AMI-100, and HS 188 + J8400.

Data in Table 9 indicate that several alloy/braze combinations completely separated through the braze at midspan in relatively few cycles after crack initiation. Generally, complete fracture was observed at the subsequent inspection period after observable crack initiation. The sixteen specimens that failed essentially completely separated at the brazed joint. Two exceptions of slow crack propagation were 316 + AMI-100 and Incoloy 800 + AMI-100, both of which initiated cracks at 88 cycles (observed at the 100 cycle inspection) and were removed at 500 cycles. The other exceptions were Incoloy 800 + Palniro 1 and 347 + AMI-400 both of which initiated a crack at 1250 cycles but separated at 2500 and 3000 cycles, respectively. Finally, Inconel 600 + Palniro 1 and Hastelloy X + CM 50 initiated cracks at 1250 cycles and completely separated at 2500 cycles and 5000 cycles, respectively.

The poorest thermal fatigue resistance, cracking in 6-18 cycles, was obtained for 316 + Nioro, 316 + 60 Alloy (2 speciment), 347 + NB50, and HS 188 + CM 52. Cracking in 88 cycles was obtained for 316 + AMI-100 and Incoloy 800 + AMI-100. Alloy/braze combinations that cracked in 1250-2250 cycles included 347 + AMI-400, Incoloy 800 + Palniro 1, Inconel 600 + Palniro 1 (2 specimens), Hastelloy X + Palniro 1, and Hastelloy X + NB30. The combinations Hastelloy X + CM 50, Hastelloy X + 75% AMI-400/25% NB30 and René 41 + AMI-300 exhibited first cracks in 2750 to 3250 cycles.

Data in Table 9 indicate that combinations with braze alloy AMI-100 provided the best thermal fatigue resistance. Three AMI-100 brazed specimens (Inconel 600, René 41, and HS 188) survived 11,000 cycles without failure. This braze alloy also provided the best fatigue resistance on 316 stainless steel, although all 316 specimens failed in relatively few thermal cycles. Only on Incoloy 800 did the AMI-100 exhibit poorer thermal fatigue resistance than the other brazing alloys. Single specimens of brazed Palniro 1 (René 41), CM 50 (Inconel 600), and J8400 (HS + 188) also survived 11,000 cycles. Palniro 1 brazed samples exhibited fatigue resistance of 1250->11,000 cycles and CM 50 samples 2750->11,000 cycles.

A summary of fatigue behavior of foil overlay BR3 specimens is contained in Table 10. Only two of the 21 BR3 specimens generated visible thermal fatigue cracks through 7000 cycles. These specimens were 347 + NB50 and Hastelloy X + CM 50; both exhibited cracks at the 7000 cycle inspection. However, all three 316 specimens and one IN 800 specimen developed blisters in the foil. Combinations 316 + AMI-100 and 316 + Nioro developed blisters in 100 cycles. Foil separation for IN 800 + Palniro 1 and 316 + 60 Alloy occurred in 500 and 3000 cycles, respectively.

Table 11 summarizes crack initiation and propagation for the five Group BR1 specimens that developed fatigue cracks prior to 7000 cycles. Locations of the three longest cracks and total cracks observed are contained in the table. The data include crack measurements on both sides of the specimen and the average crack lengths.

Thermal crack initiation and propagation for butt brazed BR2 specimens are summarized in Table 12. All cracks on these specimens occurred through the midspan braze. Accordingly, only the propagation of the midspan crack is contained in the table.

Crack propagation data for the two BR3 specimens that cracked, Hastelloy X + CM 50 and 347 + NB50, are contained in Table 13. Both specimens exhibited first cracks after 7000 thermal cycles. Three cracks were observed on the 347 specimen and one on the Hastelloy X sample.

Figure 3 shows the as-received appearance of 316 and Hastelloy X specimens typical of braze overlay BR1 specimens. Appearance of the eighteen BR1 specimens after 7000 thermal cycles is shown in Figures 4 to 6. Thermal fatigue cracks are readily visible only on specimen 316-3 in Figure 4.

The typical as-received appearance of butt-brazed BR2 specimens is shown in Figure 7. Photographs of the 23 specimens exposed for 12 to 11,000 cycles are presented in Figures 8 through 11. Extensive and/or complete separation of twelve specimens at the midspan butt braze is readily apparent in the photomacrographs.

Figure 12 shows as-received appearance of 316 and HS 188 specimens typical of foil brazed Group BR3 specimens. Foil overlays were brazed only on the radiused area of the single-edge wedge specimen. Appearance of the twenty-one Group BR1 specimens tested for 100-7000 cycles is shown in Figures 13 through 16. Blistering of the brazed foil is readily visible for 316 base alloy/braze combinations in Figure 13 and for specimen 800-8 in Figure 14.

Examination of the photographs of cycled specimens in Figures 4-16 indicates warpage of some specimens. Severe bending was also usually associated with deformation of the notch. This occurred due to interaction with the holding fixture radius at longer exposure times. However, bending of single-edge wedge specimens was not initiated by fixture interactions. Rather, warpage resulted from creep of the radiused area of the specimen during thermal cycling. The photographs in Figures 4-6, 8-11, and 12-16 show that warpage occurred only on alloys Incoloy 800 (Figures 5 and 14), and 316 (Figure 4). Alloys IN 600, Hastelloy X, 347, HS 188, and René 41 did not indicate any significant bending in any of the three test groups. Thus, warpage during thermal cycling was apparently due to the mechanical properties of the base alloy and not deformation by the fixture.

4. SUMMARY OF RESULTS

Weight change data for all three test groups at 740/25°C indicated limited oxidation for most braze/alloy combinations. High weight loss of the Group BR1 316 + 60 Alloy (specimen 316-2) combination, 1.2% in 7000 cycles, was unexplainable. It was apparent that weight loss was due to the braze alloy since other 316 base braze/alloy combinations did not exhibit high weight loss. Since specimen 316-2 was the only sample of this type in Group BR1, correlation of the high weight loss was not possible. The combination 316 + 60 Alloy was evaluated in Group BR3, but the braze alloys in this group were protected from oxidation by the foil overlay.

Thermal fatigue data on brazed overlay Group BR1 indicated the following results·

1. Five of the 18 Group BR1 specimens 316 + AMI-100 (2750 cycles), 316 + 60 Alloy (3250 cycles), Incoloy 800 + CM 52 (2750 cycles), Inconel 600 + CM 50 (4750 cycles), and Inconel 600 + Palniro 1 (4750 cycles) developed thermal fatigue cracks prior to 7000 cycles at 740/25°C.

2. No relationships between braze alloy compositions and thermal cracking was evident; thermal cracking appeared to be determined by the substrate alloys. None of the braze/alloy combinations with Hastelloy X, HS 188, and René 41 substrates exhibited cracking in 7000 cycles.

Crack initiation and propagation data for butt brazed Group BR2 specimens provided the following results·

1. Seven butt brazed BR2 specimens (Incoloy 800 + CM 52, Inconel 600 + AMI-100, Inconel 600 + CM 50, HS 188 + AMI-100, HS 188 + J8400, René 41 + Palniro 1, and René 41 + AMI-100) survived 11,000 thermal cycles at 740/25°C without cracking.

2. Early failure in 6-88 cycles occurred for alloy/braze combinations 316 + Nioro, 316 + 60 Alloy (2 specimens), 316 + AMI-100, 347 + NB50, Incoloy 800 + AMI-100, and HS 188 + CM 52. These combinations generally completely separated in relatively few thermal cycles after crack initiation.

3. Braze alloy AMI-100 exhibited the best overall resistance to cracking. Three of the five specimens brazed with AMI-100 survived 11,000 cycles without failure.

4. Thermal fatigue testing did not establish whether failure occurred within the braze alloy or at the braze-substrate interface.

Thermal fatigue data for the foil overlay Group BR3 specimens provided the following results:

1. Only two specimens, 347 + NB50 and Hastelloy X + CM 50, exhibited thermal cracking at 740/25°C. Thermal cracks were observed on both specimens at the 7000 cycles inspection.

2. All alloy/braze combinations with 316 as the substrate developed foil blisters in 100-3000 cycles. Blistering also occurred for Incoloy 800 + Palniro 1 by 500 cycles.

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Table 1

COMPOSITION OF SUBSTRATE AND BRAZE ALLOYS

Alloy	Chemical Composition, w/o C	Si	Mn	S	P	Fe	Ni	Cr	Co	Mo		Others
	Actual Composition of Substrate Alloys											
316	0.045	0.5	1.9	0.017	0.028	Bal	13.5	17.6	-	2.3		0.1Cu,0.12Ti
346	0.058	0.7	1.7	0.018	0.028	Bal	10.5	17.9	-	0.5		0.78Cb+Ta
Hastelloy X	0.08	0.5	0.6	<0.005	0.025	19.6	Bal	21.3	1.7	8.9		0.5W
Incoloy 800	0.03	0.3	1.0	0.007	-	46.0	32.2	19.7	-	-		0.37Al,0.37Ti, 0.08Cu
Inconel 600	0.06	0.2	0.2	0.007	-	8.9	74.3	16.0	-	-		0.18Cu
HS 188	0.10	0.3	0.6	0.003	0.008	1.5	22.3	21.4	Bal	-		14.5W,0.03La
René 41	0.08	0.1	<0.05	-	-	0.7	Bal	19.7	12.3	9.6		3.2Ti,1.5Al, 0.004B
	Nominal Composition of Braze Alloys											
	C	Si	Mn	S	P	Fe	Ni	Cr	Co	Pd	Au	Others
AMI-100	0.15	10.0	0.5	-	-	3.0	Bal	19.0	0.5	-	-	
AMI-300	0.10	9.5	9.5	-	-	2.3	Bal	19.5	-	-	-	
AMI-400	0.40	8.6	-	-	-	-	16.4	19.0	Bal	-	-	0.9B,4.1W
CM 50	-	3.5	-	-	-	-	Bal	-	-	-	-	1.9B
CM 52	-	4.5	-	-	-	1.5	Bal	-	-	-	-	3.1B
NB30	-	10.2	1.0	-	-	0.4	Bal	19.0	-	-	-	
NB50	-	-	-	-	-	-	Bal	13.0	-	-	-	10P
J8400	0.40	8.0	-	-	-	-	21.0	21.0	Bal	-	-	4.0W,0.8B
Nioro	-	-	-	-	-	-	18.0	-	-	-	72.0	
Palniro 1	-	-	-	-	-	-	25.0	-	-	25.0	50.0	
60 Alloy	-	-	-	-	-	-	6.0	-	-	-		94.0Cu

Table 2

DIMENSIONS AND IDENTIFICATION OF BRAZE OVERLAY TEST GROUP BR1

Alloy/Braze System	Specimen No.	Edge Radius, mm	Initial Dimensions, mm Thickness	Width	Length	Total Exposure, Cycles
Hastelloy X + Palniro 1	X-1	0.71	6.00	25.65	100.30	7000
Hastelloy X + 25% NB30/75% AMI-400	X-2	0.91	6.00	25.68	100.33	7000
Hastelloy X + CM 50	X-3	0.83	6.01	25.53	100.20	7000
Inconel 600 + CM 50	600-1	0.94	5.99	25.27	100.00	7000
Inconel 600 + Palniro 1	600-2	0.83	5.98	25.25	99.12	7000
Inconel 600 + AMI-100	600-3	6.83	5.99	25.27	99.87	7000
Incoloy 800 + AMI-100	800-1	0.99	5.67	25.20	100.10	7000
Incoloy 800 + Palniro 1	800-2	0.79	6.00	25.20	99.82	7000
Incoloy 800 + CM 52	800-3	0.79	5.97	25.60	99.87	7000
316 + Nioro	316-1	0.74	5.96	24.71	100.05	7000
316 + 60 Alloy	316-2	0.83	5.90	24.76	100.08	7000
316 + AMI-100	316-3	0.71	5.99	24.71	100.13	7000
HS 188 + CM 52	188-1	0.66	5.89	25.65	100.38	7000
HS 188 + J8400	188-2	0.86	5.78	25.17	100.38	7000
HS 188 + AMI-100	188-3	1.09	5.88	25.20	100.43	7000
René 41 + AMI-300	41-1	0.66	6.04	25.45	100.38	7000
René 41 + AMI-100	41-2	0.79	5.91	25.04	100.30	7000
René 41 + Palniro 1	41-3	0.76	5.90	24.99	100.20	7000

Table 3

DIMENSIONS AND IDENTIFICATION OF BUTT BRAZED TEST GROUP BR2

Alloy/Braze System	Specimen No.	Edge Radius, mm	Initial Dimensions, mm Thick-ness	Width	Length	Total Exposure, Cycles
Hastelloy X + Palniro 1	X-4	0.69	6.02	25.20	99.62	2,500
Hastelloy X + CM 50	X-5	0.69	5.96	25.58	99.49	5,000
Hastelloy X + 25% NB30/75% AMI-400	X-6	0.71	6.03	25.58	99.57	3,500
Hastelloy X + NB30	X-7	0.89	6.03	25.65	99.57	2,500
Inconel 600 + AMI-100	600-4	1.02	5.80	24.92	99.95	11,000
Inconel 600 + Palniro 1	600-5	0.86	5.90	24.94	99.98	2,475
Inconel 600 + Palniro 1	600-6	1.14	5.70	24.92	99.74	2,000
Inconel 600 + CM 50	600-7	1.19	5.93	24.87	99.59	11,000
Incoloy 800 + AMI-100	800-4	1.17	5.86	23.95	98.93	500
Incoloy 800 + Palniro 1	800-5	1.18	5.86	23.95	98.78	2,000
Incoloy 800 + CM 52	800-6	1.19	5.79	23.72	98.83	11,000
316 + AMI-100	316-4	0.89	5.94	23.65	98.83	500
316 + Nioro	316-5	0.76	5.88	24.51	98.83	25
316 + 60 Alloy	316-6	1.14	5.98	24.31	99.03	75
316 + 60 Alloy	316-7	1.14	5.54	23.82	99.49	50
HS 188 + AMI-100	188-4	1.17	5.71	24.21	99.64	11,000
HS 188 + J8400	188-5	0.89	5.95	24.56	99.59	11,000
HS 188 + CM 52	188-6	0.86	5.97	23.37	99.54	25
René 41 + AMI-100	41-4	0.74	6.03	24.36	99.77	11,000
René 41 + Palniro 1	41-5	0.74	5.72	24.66	99.67	11,000
René 41 + AMI-300	41-6	1.14	6.02	24.66	99.26	3,000
347 + NB50	347-1	1.09	5.96	24.05	98.88	12
347 + AMI-400	347-2	1.04	5.70	24.08	98.91	3,000

Table 4

DIMENSIONS AND IDENTIFICATION OF BRAZED FOIL TEST GROUP BR3

Alloy/Braze System	Specimen No.	Edge Radius, mm	Initial Dimensions, mm Thickness	Width	Length	Total Exposure, Cycles
Hastelloy X + Palniro 1	X-8	0.69	5.99	25.15	100.00	7000
Hastelloy X + CM 50	X-9	0.71	5.93	25.45	100.03	7000
Hastelloy X + 25% NB30/75% AMI-400	X-10	0.76	5.96	25.15	100.00	7000
Hastelloy X + NB30	X-11	0.83	5.90	25.27	99.97	7000
Inconel 600 + AMI-100	600-8	0.71	5.67	25.48	99.92	7000
Inconel 600 + Palniro 1	600-9	0.79	5.81	25.58	99.97	7000
Inconel 600 + CM 50	600-10	0.94	5.77	25.50	100.28	7000
Incoloy 800 + AMI-100	800-7	0.83	5.87	24.77	100.03	7000
Incoloy 800 + Palniro 1	800-8	0.83	5.93	25.53	99.90	500
Incoloy 800 + CM 52	800-9	0.97	5.99	25.12	100.00	7000
316 + AMI-100	316-8	0.66	5.73	25.02	100.56	100
316 + Nioro	316-9	0.84	5.86	25.17	100.51	100
316 + 60 Alloy	316-10	0.71	5.82	25.04	100.03	3000
HS 188 + AMI-100	188-7	0.64	5.90	25.42	100.28	7000
HS 188 + J8400	188-8	0.66	5.97	25.20	100.28	7000
HS 188 + CM 52	188-9	0.74	5.93	25.55	100.25	7000
René 41 + AMI-100	41-7	0.64	5.95	24.13	100.08	7000
René 41 + Palniro 1	41-8	0.66	5.81	24.94	100.13	7000
René 41 + AMI-300	41-9	0.74	5.72	25.30	100.08	7000
347 + NB50	347-3	0.61	6.06	25.02	100.03	7000
347 + AMI-400	347-4	0.69	5.36	25.12	99.95	7000

Table 5

WEIGHT CHANGE DATA FOR BR1 SPECIMENS

Material	Specimen No.	Starting Weight, g	Weight Change at Given Cycles, %							
			100	150	200	300	400	500	700	1000
Hastelloy X + Palniro 1	X-1	109.9883	.003	.003	.003	.003	.003	.003	.003	.001
Hastelloy X + 25% NB30/75% AMI-400	X-2	110.7861	.005	.005	.006	.006	.005	.005	.005	.002
Hastelloy X + CM 50 (Spec. 1)	X-3	110.0290	.005	.005	.006	.006	.006	.006	.005	.003
Inconel 600 + CM 50	600-1	110 6743	.004	.004	.004	.003	.002	.001	.001	-.004
Inconel 600 + Palniro 1	600-2	109.3247	.005	.006	.006	.005	.004	.003	.002	-.004
Inconel 600 + AMI-100	600-3	110.0069	.004	.002	0	-.002	-.003	-.005	-.010	-.014
Incoloy 800 + AMI-100	800-1	103.8184	.009	.010	.010	.013	.012	.012	003	-.005
Incoloy 800 + Palniro 1 (Spec. 1)	800-2	104.0549	.008	.009	.009	.008	.009	.004	0	-.007
Incoloy 800 + CM 52	800-3	104.5183	.010	.012	.013	.011	.009	.008	.001	-.002
316 + Nioro	316-1	100.9996	008	.008	.008	.006	.007	.007	.001	-.006
316 + 60 Alloy	316-2	100.0595	-.396	-.526	-.665	-.729	-.730	-.749	-.766	-.776
316 + AMI-100	316-3	101.0661	.009	.010	.006	.004	.005	.005	-.012	-.023
HS 188 + CM 52	188-1	120.4991	.005	.004	.004	.005	.004	.003	.004	.003
HS 188 + J8400	188-2	115.3518	.003	.003	.002	.004	.003	.004	.002	.002
HS 188 + AMI-100	188-3	118.0863	.004	.004	.005	.005	.004	.004	.003	0
René 41 + AMI-300	41-1	110.3641	.003	.003	.003	.003	.002	001	001	0
René 41 + AMI-100	41-2	106.3923	.003	.003	.003	002	.002	.001	0	-.001
René 41 + Palniro 1	41-3	105.1614	.003	.003	.002	.002	.002	.002	.002	001

Table 5 (cont.)

Material	Specimen No.	Starting Weight, g	Weight Change at Given Cycles, %							
			1500	2000	2500	3000	3500	4000	4500	5000
Hastelloy X + Palniro 1	X-1	109.9883	-.005	-.010	-.016	-.027	-.034	-.048	-.056	-.067
Hastelloy X + 25% NB30/75% AMI-400	X-2	110.7861	-.004	-.009	-.016	-.026	-.035	-.048	-.064	-.081
Hastelloy X + CM 50 (Spec. 1)	X-3	110.0290	-.003	-.009	-.016	-.025	-.034	-.051	-.062	-.075
Inconel 600 + CM 50	600-1	110.6743	-.003	-.017	-.032	-.060	-.086	-.113	-.151	-.178
Inconel 600 + Palniro 1	600-2	109.3247	-.014	-.029	-.049	-.074	-.096	-.126	-.147	-.176
Inconel 600 + AMI-100	600-3	110.0069	-.014	-.031	-.046	-.077	-.096	-.122	-.140	-.165
Incoloy 800 + AMI-100	800-1	103.8184	-.015	-.030	-.046	-.064	-.082	-.118	-.147	-.179
Incoloy 800 + Palniro 1 (Spec. 1)	800-2	104.0549	-.013	-.032	-.076	-.098	-.122	-.157	-.177	-.219
Incoloy 800 + CM 52	800-3	104.5183	-.007	-.022	-.050	-.082	-.098	-.153	-.189	-.225
316 + Nioro	316-1	100.9996	-.018	-.036	-.070	-.087	-.113	-.145	-.176	-.202
316 + 60 Alloy	316-2	100.0595	-.778	-.807	-.837	-.890	-.928	-.980	-1.013	-1.080
316 + AMI-100	316-3	101.0661	-.046	-.079	-.106	-.156	-.197	-.258	-.296	-.342
HS 188 + CM 52	188-1	120.4991	-.003	-.007	-.011	-.016	-.021	-.032	-.032	-.043
HS 188 + J8400	188-2	115.3518	-.002	-.009	-.016	-.029	-.035	-.043	-.046	-.057
HS 188 + AMI-100	188-3	118.0863	-.006	-.011	-.018	-.026	-.033	-.045	-.063	-.069
René 41 + AMI-300	41-1	110.3641	-.003	-.003	-.006	-.014	-.024	-.032	-.045	-.054
René 41 + AMI-100	41-2	106.3923	-.007	-.011	-.014	-.019	-.025	-.033	-.041	-.055
René 41 + Palniro 1	41-3	105.1614	-.002	-.006	-.010	-.016	-.023	-.030	-.036	-.048

Table 5 (cont.)

Material	Specimen No.	Starting Weight, g	Weight Change at Given Cycles, %			
			5500	6000	6500	7000
Hastelloy X + Palniro 1	X-1	109.9883	-.084	-.094	-.111	-.124
Hastelloy X + 25% NB30/75% AMI-400	X-2	110.7861	-.095	-.106	-.123	-.132
Hastelloy X + CM 50 (Spec. 1)	X-3	110.0290	-.090	-.104	-.119	-.130
Inconel 600 + CM 50	600-1	110.6743	-.207	-.236	-.261	-.295
Inconel 600 + Palniro 1	600-2	109.3247	-.203	-.233	-.258	-.285
Inconel 600 + AMI-100	600-3	110.0069	-.191	-.222	-.244	-.272
Incoloy 800 + AMI-100	800-1	103.8184	-.207	-.239	-.277	-.309
Incoloy 800 + Palniro 1 (Spec. 1)	800-2	104.0549	-.235	-.281	-.312	-.345
Incoloy 800 + CM 52	800-3	104.5183	-.290	-.337	-.373	-.427
316 + Nioro	316-1	100.9996	-.234	-.273	-.300	-.355
316 + 60 Alloy	316-2	100.0595	-1.120	-1.162	-1.184	-1.216
316 + AMI-100	316-3	101.0661	-.376	-.451	-.475	-.510
HS 188 + CM 52	188-1	120.4991	-.053	-.070	-.079	-.085
HS 188 + J8400	188-2	115.3518	-.070	-.085	-.096	-.102
HS 188 + AMI-100	188-3	118.0863	-.083	-.098	-.110	-.116
René 41 + AMI-300	41-1	110.3641	-.064	-.073	-.082	-.085
René 41 + AMI-100	41-2	106.3923	-.061	-.075	-.086	-.096
René 41 + Palniro 1	41-3	105.1614	-.060	-.070	-.084	-.088

Table 6

WEIGHT CHANGE DATA FOR BR2 SPECIMENS

Material	Specimen No.	Starting Weight, g	Weight Change at Given Cycles, %												
			12	25	37	50	75	100	150	200	300	400	500	700	1000
Hastelloy X + Palniro 1	X-4	105.2435						.002	.002	.002	.002	.002	.003	.002	-.001
Hastelloy X + CM 50	X-5[a]	107.3080						.002	.003	.003	.003	.003	.003	.001	-.001
Hastelloy X + 25% NB30/75% AMI-400	X-6	108.0463						.002	.002	.002	.002	.002	.002	.001	.001
Hastelloy X + NB30	X-7	109.3923						.002	.002	.003	.003	.003	.003	.003	.003
Inconel 600 + AMI-100	600-4	104.7066						.002	.002	.002	.005	.003	.001	-.002	-.004
Inconel 600 + Palniro 1	600-5[a]	103.9325						.001	.001	.001	.002	.001	0	-.001	-.003
Inconel 600 + Palniro 1	600-6	103.2547						.003	.003	.003	.003	.002	.002	-.001	-.003
Inconel 600 + CM 50	600-7	105.2728						.002	.002	.002	.002	.002	.001	-.002	-.008
Incoloy 800 + AMI-100	800-4	92.5118						.003	.003	.003	.004	.005	007	-	-
Incoloy 800 + Palniro 1	800-5[b]	93.4612				.003		.003	.003	.004	.004	.005	.005	.007	.008
Incoloy 800 + CM 52	800-6	92.7587						.004	.004	.004	.004	.004	.005	.006	.004
316 + AMI-100	316-4	94.0526						.003	.003	.003	.003	.003	.003	-	-
316 + Nioro	316-5	93.9690		.005				-	-	-	-	-	-	-	-
316 + 60 Alloy	316-6[a]	90.0137						.004	-	-	-	-	-	-	-
316 + 60 Alloy	316-7	97.4824				.009		-	-	-	-	-	-	-	-
HS 188 + AMI-100	188-4	108.1693						.006	.005	.004	.004	.003	.003	.002	.001
HS 188 + J8400	188-5	111.1705						.005	.004	.003	.004	.003	.003	.003	.002
HS 188 + CM 52	188-6	105.8470		.003				-		-	-		-	-	-
René 41 + AMI-100	41-4	102.5588						.003	.003	.003	.003	.003	.003	.001	-.001
René 41 + Palniro 1	41-5[c]	99.3516				.002		.002	-	.003	.003	.003	-	.001[d]	.001[e]
René 41 + AMI-300	41-6	102.3860						.004	.002	.002	.003	.004	.004	.001	0
347 + NB50	347-1	94.7081	.005					-		-	-		-	-	-
347 + AMI-400	347-2	91.8464						.003	.002	.002	.002	.002	.001	-.005	-.012

See page 22 for footnotes

Table 6 (cont.)

Material	Specimen No.	Starting Weight, g	Weight Change at Given Cycles, %							
			1500	2000	2500	3000	3500	4000	4500	5000
Hastelloy X + Palniro 1	X-4	105.2435	-.002	-.008	-.017	-	-	-	-	-
Hastelloy X + CM 50	X-5[a]	107.3080	-.002	-.013	-.021	-.034	-.056	-.068	-.075	-.125
Hastelloy X + 25% NB30/75% AMI-400	X-6	108.0463	-.001	-.009	-.015	-.021	-.034	-	-	-
Hastelloy X + NB30	X-7	109.3923	-.005	-.007	-.017	-	-	-	-	-
Inconel 600 + AMI-100	600-4	104.7066	-.014	-.034	-.052	-.080	-.116	-.141	-.159	-.185
Inconel 600 + Palniro 1	600-5[a]	103.9325	-.013	-.029	-.043	-	-	-	-	-
Inconel 600 + Palniro 1	600-6	103.2547	-.014	-.027	-	-	-	-	-	-
Inconel 600 + CM 50	600-7	105.2728	-.014	-.026	-.043	-.063	-.088	-.113	-.131	-.162
Incoloy 800 + AMI-100	800-4	92.5118	-	-	-	-	-	-	-	-
Incoloy 800 + Palniro 1	800-5[b]	93.4612	-.003	-.012	-	-	-	-	-	-
Incoloy 800 + CM 52	800-6	92.7587	-.001	-.015	-.032	-.060	-.093	-.125	-.153	-.191
316 + AMI-100	316-4	94.0526	-	-	-	-	-	-	-	-
316 + Nioro	316-5	93.9690	-	-	-	-	-	-	-	-
316 + 60 Alloy	316-6[a]	90.0137	-	-	-	-	-	-	-	-
316 + 60 Alloy	316-7	97.4824	-	-	-	-	-	-	-	-
HS 188 + AMI-100	188-4	108.1693	-.010	-.005	-.014	-.020	-.032	-.041	-.049	-.064
HS 188 + J8400	188-5	111.1705	-.002	-.007	-.017	-.021	-.041	-.050	-.055	-.072
HS 188 + CM 52	188-6	105.8470	-	-	-	-	-	-	-	-
René 41 + AMI-100	41-4	102.5588	-.002	-.009	-.016	-.020	-.029	-.035	-.043	-.056
René 41 + Palniro 1	41-5[c]	99.3516	-.003	-.007	-.012	-.021	-.034	-.041	-.048	-.059
René 41 + AMI-300	41-6	102.3860	-.002	-.012	-.019	-.022	-	-	-	-
347 + NB50	347-1	94.7081	-	-	-	-	-	-	-	-
347 + AMI-400	347-2	91.8464	-.028	-.044	-.073	-.083	-	-	-	-

See page 22 for footnotes

Table 6 (cont.)

Material	Specimen No.	Starting Weight, g	Weight Change at Given Cycles, %								
			5500	6000	6500	7000	7500	8000	8500	9000	9500
Hastelloy X + Palniro 1	X-4	105.2435	-	-							
Hastelloy X + CM 50	X-5[a]	107.3080	-	-							
Hastelloy X + 25% NB30/75% AMI-400	X-6	108.0463	-	-							
Hastelloy X + NB30	X-7	109.3923	-	-							
Inconel 600 + AMI-100	600-4	104.7066	-.213	-.243	-.279	-.302	-.377	-.401	-.416	-.433	-.448
Inconel 600 + Palniro 1	600-5[a]	103.9325	-	-							
Inconel 600 + Palniro 1	600-6	103.2547	-	-							
Inconel 600 + CM 50	600-7	105.2728	-.195	-.224	-.255	-.278	-.342	-.372	-.387	-.403	-.429
Incoloy 800 + AMI-100	800-4	92.5118	-	-							
Incoloy 800 + Palniro 1	800-5[b]	93.4612	-	-							
Incoloy 800 + CM 52	800-6	92.7587	-.241	-.286	-.344	-.383	-.534	-.569	-.598	-.603	-.615
316 + AMI-100	316-4	94.0526	-	-							
316 + Nioro	316-5	93.9690	-	-							
316 + 60 Alloy	316-6[a]	90.0137	-	-							
316 + 60 Alloy	316-7	97.4824	-	-							
HS 188 + AMI-100	188-4	108.1693	-.085	-.103	-.121	-.133	-.206	-.217	-.228	-.236	-.246
HS 188 + J8400	188-5	111.1705	-.083	-.090	-.103	-.114	-.123	-.136	-.146	-.156	-.171
HS 188 + CM 52	188-6	105.8470	-	-							
René 41 + AMI-100	41-4	102.5588	-.065	-.074	-.083	-.094	-.165	-.178	-.186	-.196	-.205
René 41 + Palniro 1	41-5[c]	99.3516	-.072	-.080	-.093	-.104	-.227	-.242	-.250	-.257	-.274
René 41 + AMI-300	41-6	102.3860	-	-							
347 + NB50	347-1	94.7081	-	-							
347 + AMI-400	347-2	91.8464	-	-							

See page 22 for footnotes

Table 6 (cont.)

Material	Specimen No.	Starting Weight, g	Weight Change at Given Cycles, %		
			10,000	10,500	11,000
Hastelloy X + Palniro 1	X-4	105.2435			
Hastelloy X + CM 50	X-5[a]	107.3080			
Hastelloy X + 25% NB30/75% AMI-400	X-6	108.0463			
Hastelloy X + NB30	X-7	109.3923			
Inconel 600 + AMI-100	600-4	104.7066	-.468	-.501	-.523
Inconel 600 + Palniro 1	600-5[a]	103.9325			
Inconel 600 + Palniro 1	600-6	103.2547			
Inconel 600 + CM 50	600-7	105.2728	-.453	-.484	-.506
Incoloy 800 + AMI-100	800-4	92.5118			
Incoloy 800 + Palniro 1	800-5[b]	93.4612			
Incoloy 800 + CM 52	800-6	92.7587	-.642	-.664	-.698
316 + AMI-100	316-4	94.0526			
316 + Nioro	316-5	93.9690			
316 + 60 Alloy	316-6[a]	90.0137			
316 + 60 Alloy	316-7	97.4824			
HS 188 + AMI-100	188-4	108.1693	-.255	-.264	-.272
HS 188 + J8400	188-5	111.1705	-.181	-.190	-.199
HS 188 + CM 52	188-6	105.8470			
René 41 + AMI-100	41-4	102.5588	-.213	-.223	-.231
René 41 + Palniro 1	41-5[c]	99.3516	-.283	-.292	-.303
René 41 + AMI-300	41-6	102.3860			
347 + NB50	347-1	94.7081			
347 + AMI-400	347-2	91.8464			

[a] Specimen added after 25 cycles

[b] Specimen added after 50 cycles

[c] Specimen added after 100 cycles

[d] Data for 600 cycles

[e] Data for 900 cycles

Table 7

WEIGHT CHANGE DATA FOR BRAZE FOIL BR3 SPECIMENS

Material	Specimen No.	Starting Weight, g	Weight Change at Given Cycle, %									
			100	200	300	500	700	1000	1500	2000	2500	3000
Hastelloy X + Palniro 1	X-8	107.4430	.002	.002	.002	.002	-.001	-.002	-.003	-.009	-.010	-.015
Hastelloy X + CM 50	X-9	107.3658	.001	.001	-.001	-.001	-.001	-.004	-.019	-.027	-.032	-.037
Hastelloy X + 25% NB30/75% AMI-400	X-10	106.3250	.001	.007	.001	0	-.002	-.002	-.002	-.010	-.015	-.021
Hastelloy X + NB30	X-11	106.0165	0	.002	.001	-.001	-.001	-.003	-.007	-.015	-.021	-.028
Inconel 600 + AMI-100	600-8	104.3981	.005	.005	.004	.004	.002	-.001	-.004	-.017	-.027	-.043
Inconel 600 + Palniro 1[a]	600-9	109.3032	-	.003[b]	.002[c]	.001[d]	0	-.002	-.004	-.012	-.025	-.039
Inconel 600 + CM 50	600-10	107.7507	001	.003	.002	0	-.004	-.001	-.011	-.021	-.034	-.047
Incoloy 800 + AMI-100	800-7	99.3643	.004	.003	.002	.001	.001	.003	-.011	-.033	-.041	-.062
Incoloy 800 + Palniro 1[e]	800-8	102.8561	-	-	-	.005	-	-	-	-	-	-
Incoloy 800 + CM 52[a]	800-9	103.1475	-	.004[b]	.008[c]	.004[d]	.005	.004	.001	-.009	-.017	-.030
316 + AMI-100[f]	316-8	98.8648	.011	-	-	-	-	-	-	-	-	-
316 + Nioro[f]	316-9	103.0986	.043	-	-	-	-	-	-	-	-	-
316 + 60 Alloy[g]	316-10	100.1455	.005	.004	.008	.003	.001	.005	-.005	-.017	-.029	-.052
HS 188 + AMI-100	188-7	97.2268	.004	.004	.005	.004	.003	0	-.002	-.010	-.014	-.021
HS 188 + J8400	188-8	112.7811	.003	.003	.002	.001	-.001	-.002	-.012	-.019	-.020	-.024
HS 188 + CM 52	188-9	107.8307	.004	.001	.002	.001	-.003	-.002	-.006	-.016	-.023	-.031
René 41 + AMI-100	41-7	107.5890	.002	.001	.002	.001	-.003	-.003	-.003	-.008	-.010	-.011
René 41 + Palniro 1	41-8	107.5468	.001	.003	.003	.001	-.002	-.001	-.004	-.008	-.012	-.018
René 41 + AMI-300	41-9	108.8861	0	.004	.005	.006	.003	.003	.001	-.002	-.005	-.015
347 + NB50	347-3	98.7812	.002	.004	.002	0	-.005	-.003	-.010	-.020	-.030	-.058
347 + AMI-400	347-4	92.9204	0	.007	.007	.002	-.002	-.005	-.023	-.050	-.060	-.080

See next page for footnotes

Table 7 (cont.)

Material	Specimen No.	Starting Weight, g	Weight Change at Given Cycle, %							
			3500	4000	4500	5000	5500	6000	6500	7000
Hastelloy X + Palniro 1	X-8	107.4430	-.022	-.035	-.046	-.054	-.072	-.080	-.087	-.099
Hastelloy X + CM 50	X-9	107.3658	-.047	-.056	-.068	-.072	-.092	-.099	-.109	-.118
Hastelloy X + 25% NB30/75% AMI-400	X-10	106.3250	-.028	-.035	-.045	-.052	-.069	-.077	-.086	-.095
Hastelloy X + NB30	X-11	106.0165	-.034	-.041	-.052	-.055	-.066	-.076	-.083	-.094
Inconel 600 + AMI-100	600-8	104.3981	-.059	-.079	-.102	-.109	-.126	-.139	-.151	-.174
Inconel 600 + Palniro 1[a]	600-9	109.3032	-.052	-.072	-.089	-.102	-.117	-.132	-.143	-.168
Inconel 600 + CM 50	600-10	107.7507	-.072	-.088	-.117	-.133	-.160	-.176	-.185	-.202
Incoloy 800 + AMI-100	800-7	99.3643	-.095	-.111	-.138	-.153	-.168	-.189	-.210	-.238
Incoloy 800 + Palniro 1[e]	800-8	102.8561	-	-	-	-	-	-	-	-
Incoloy 800 + CM 52[a]	800-9	103.1475	-.055	-.074	-.099	-.111	-.136	-.156	-.178	-.197
316 + AMI-100[f]	316-8	98.8648	-	-	-	-	-	-	-	-
316 + Nioro[f]	316-9	103.0986	-	-	-	-	-	-	-	-
316 + 60 Alloy[g]	316-10	100.1455	-	-	-	-	-	-	-	-
HS 188 + AMI-100	188-7	97.2268	-.030	-.039	-.045	-.049	-.057	-.066	-.069	-.078
HS 188 + J8400	188-8	112.7811	-.034	-.041	-.049	-.047	-.060	-.068	-.074	-.083
HS 188 + CM 52	188-9	107.8307	-.041	-.045	-.051	-.054	-.061	-.068	-.074	-.081
René 41 + AMI-100	41-7	107.5890	-.019	-.023	-.031	-.033	-.046	-.053	-.056	-.063
René 41 + Palniro 1	41-8	107.5468	-.023	-.031	-.038	-.041	-.056	-.059	-.062	-.065
René 41 + AMI-300	41-9	108.8861	-.019	-.027	-.031	-.035	-.042	-.049	-.052	-.057
347 + NB50	347-3	98.7812	-.085	-.127	-.156	-.173	-.214	-.242	-.263	-.299
347 + AMI-400	347-4	92.9204	-.111	-.135	-.161	-.184	-.220	-.243	-.273	-.303

[a] Nos 600-9 and 800-10 added after 100 cycles for 6900 cycle total exposure
[b] 100 cycles
[c] 200 cycles
[d] 400 cycles
[e] Added after 3000 cycles, removed after 3500 cycles due to blistering
[f] Removed at 100 cycles due to blistering on radius
[g] Removed at 3000 cycles due to blistering on radius

Table 8

SUMMARY OF CRACK INITIATION IN BRAZED OVERLAY GROUP BR1 SPECIMENS

Alloy/Braze System	Specimen No.	Cycles to First Crack[a]
316 + AMI-100	316-3	2750
316 + 60 Alloy	316-2	3250
316 + Nioro	316-1	>7000
Incoloy 800 + CM 52	800-3	2750
Incoloy 800 + AMI-100	800-1	>7000
Incoloy 800 + Palniro 1	800-2	>7000
Inconel 600 + CM50	600-1	4750
Inconel 600 + Palniro 1	600-2	4750
Inconel 600 + AMI-100	600-3	>7000
Hastelloy X + Palniro 1	X1	>7000
Hastelloy X + 75% AMI-400/ 25% NB30	X2	>7000
Hastelloy X + CM50	X3	>7000
HS 188 + CM 52	188-1	>7000
HS 188 + J8400	188-2	>7000
HS 188 + AMI-100	188-3	>7000
René 41 + AMI-300	41-1	>7000
René 41 + AMI-100	41-2	>7000
René 41 + Palniro 1	41-3	>7000

[a]All samples exposed 7000 cycles.

Table 9

SUMMARY OF CRACK INITIATION IN BUTT BRAZED GROUP BR2 SPECIMENS

Alloy/Braze System	Specimen No.	Cycles to First Crack	Cycles to Separation
316 + Nioro	316-5	18	25[a]
316 + 60 Alloy	316-6	18	75[a]
316 + 60 Alloy	316-7	18	50[a]
316 + AMI-100	316-4	88	500[b]
347 + NB50	347-1	6	12[a]
347 + AMI-400	347-2	1,250	3,000[a]
Incoloy 800 + AMI-100	800-4	88	500[b]
Incoloy 800 + Palniro 1	800-5	1,250	2,000[b]
Incoloy 800 + CM52	800-6	>11,000	>11,000
Hastelloy X + Palniro 1	X-4	1,250	2,500[a]
Hastelloy X + Nb-30	X-7	2,250	2,500[a]
Hastelloy X + CM50	X-5	2,750	5,000[a]
Hastelloy X + 75% AMI-400/ 25% NB30	X-6	3,250	3,500[a]
Inconel 600 + Palniro 1	600-6	1,250	2,000[b]
Inconel 600 + Palniro 1	600-5	1,250	2,500[a]
Inconel 600 + AMI-100	600-4	>11,000	>11,000
Inconel 600 + CM50	600-7	>11,000	>11,000
HS 188 + CM52	188-6	18	25[a]
HS 188 + AMI-100	188-4	>11,000	>11,000
HS 188 + J8400	188-5	>11,000	>11,000
René 41 + AMI-300	41-6	2,750	3,000[a]
René 41 + Palniro 1	41-5	>11,000	>11,000
René 41 + AMI-100	41-4	>11,000	>11,000

[a]Completely separated at braze.

[b]Extensive cracking at braze.

Table 10

SUMMARY OF CRACK INITIATION IN BRAZED FOIL OVERLAY GROUP BR3 SPECIMENS

Alloy/Braze System	Specimen No.	Cycles to First Crack	Total Exposure Cycles
316 + AMI-100	316-8	>100	100[a]
316 + Nioro	316-9	>100	100[a]
316 + 60 Alloy	316-10	>3000	3000[b]
347 + NB50	347-3	6750	7000
347 + AMI-400	347-4	>7000	7000
Hastelloy X + CM50	X-9	6750	7000
Hastelloy X + Palniro 1	X-8	>7000	7000
Hastelloy X + 75% AMI-400/ 25% NB30	X-10	>7000	7000
Hastelloy X + Nb-30	X-11	>7000	7000
Inconel 600 + AMI-100	600-8	>7000	7000
Inconel 600 + Palniro 1	600-9	>6900	6900
Inconel 600 + CM50	600-10	>7000	7000
Incoloy 800 + AMI-100	800-7	>7000	7000
Incoloy 800 + Palniro 1	800-8	>500	500[c]
Incoloy 800 + CM52	800-9	>7000	7000
HS 188 + AMI-100	188-7	>7000	7000
HS 188 + J8400	188-8	>7000	7000
HS 188 + CM52	188-9	>7000	7000
René 41 + AMI-100	41-7	>7000	7000
René 41 + Palniro 1	41-8	>7000	7000
René 41 + AMI-300	41-9	>7000	7000

[a]Removed at 100 cycles due to blisters in brazed foil.

[b]Removed at 3000 cycles due to blisters in brazed foil.

[c]Inserted at 3000 cycles and removed at 3500 cycles due to foil blisters.

Table 11

CRACK PROPAGATION FOR BRAZED OVERLAY GROUP BR1 SPECIMENS

Edge Radius, mm	Cycles	Crack Length, mm: 1st Crack Front	1st Crack Back	1st Crack Avg	2nd Crack Front	2nd Crack Back	2nd Crack Avg	3rd Crack Front	3rd Crack Back	3rd Crack Avg	Total Cracks Observed
					Specimen 316-3: 316 + AMI-100						
Distance from bottom, mm				53.3			60.5			68.3	
0.71	2500	No cracks									
	3000	2.03	2.03	2.03	1.78	1.52	1.65	1.27	1.27	1.27	3
	3500	2.03	2.03	2.03	2.29	1.78	2.04	1.27	1.27	1.27	5
	4000	3.05	3.81	3.43	2.79	2.79	2.79	1.27	1.52	1.40	5
	4500	3.05	3.81	3.43	2.79	2.79	2.79	1.27	1.52	1.40	8
	5000	3.56	3.81	3.68	2.79	2.79	2.79	2.54	2.54	2.54	8
	5500	3.56	3.81	3.68	3.05	2.79	2.92	2.54	2.54	2.54	8
	6000	3.56	3.81	3.68	3.05	2.79	2.92	2.79	2.54	2.66	8
	6500	4.06	4.32	4.19	3.05	2.79	2.92	2.79	2.54	2.66	8
	7000	4.06	4.57	4.32	3.05	2.79	2.92	3.30	4.06	3.68	8
					Specimen 316-2: 316 + 60 Alloy						
Distance from bottom, mm				47.2			52.3			63.5	
0.81	3000	No cracks									
	3500	2.29	1.78	2.04	2.29	2.79	2.54	0.76	0.76	0.76	20
	4000	2.29	2.03	2.16	2.03	2.79	2.41	1.52	1.27	1.40	20
	4500	2.29	2.03	2.16	2.29	2.79	2.54	1.52	1.27	1.40	24
	5000	2.29	2.03	2.16	2.29	2.79	2.54	2.03	2.03	2.03	30
	5500	2.29	2.03	2.16	2.29	2.79	2.54	3.05	2.03	2.54	>30
	6000	2.29	2.03	2.16	2.29	3.05	2.67	3.05	2.03	2.54	>30
	6500	2.29	2.03	2.16	2.29	3.05	2.67	3.05	2.03	2.54	>30
	7000	2.29	2.03	2.16	2.29	3.05	2.67	3.05	2.03	2.54	>30

Table 11 (cont.)

Edge Radius, mm	Cycles	Crack Length, mm: 1st Crack Front	1st Crack Back	1st Crack Avg	2nd Crack Front	2nd Crack Back	2nd Crack Avg	3rd Crack Front	3rd Crack Back	3rd Crack Avg	Total Cracks Observed
				Specimen 800-3: IN-800 + CM 52							
Distance from bottom, mm				30.2			44.5			74.7	
0.66	2500	No cracks									
	3000	1.52	1.52	1.52	1.52	0.25	0.88	1.27	1.52	1.40	3
	3500	1.52	1.52	1.52	1.52	0.25	0.88	1.27	2.03	1.65	3
	4000	1.78	1.52	1.65	2.03	0.76	1.40	1.52	2.54	2.03	4
	4500	1.78	1.52	1.65	2.03	1.52	1.78	2.54	2.54	2.54	4
	5000	1.78	1.52	1.65	2.29	1.52	1.91	2.54	2.79	2.66	4
	5500	2.03	2.03	2.03	2.29	2.54	2.42	2.54	2.79	2.66	5
	6000	2.03	2.03	2.03	2.29	2.54	2.42	3.05	3.05	3.05	5
	6500	2.03	2.03	2.03	2.54	2.54	2.54	3.56	3.05	3.31	5
	7000	3.05	2.54	2.80	3.05	2.79	2.92	3.56	3.05	3.31	6
				Specimen 600-1: IN-600 + CM 50							
Distance from bottom, mm				41.4			50.8			57.2	
0.94	4500	No cracks									
	5000	0.25	0.25	0.25	-	-		-	-		1
	5500	0.76	0.25	0.51	-	-		-	-		1
	6000	1.02	0.76	0.89	1.02	1.02	1.02	1.02	1.02	1.02	7
	6500	1.02	0.76	0.89	1.02	1.02	1.02	1.02	1.02	1.02	10
	7000	1.27	1.02	1.14	1.78	1.78	1.78	1.02	1.02	1.02	13
				Specimen 600-2: IN-600 + Palniro 1							
Distance from bottom, mm				25.4			45.0			71.4	
0.81	4500	No cracks									
	5000	1.52	1.52	1.52	1.02	1.27	1.14	1.02	0.51	0.76	6
	5500	1.52	1.52	1.52	1.02	1.27	1.14	1.02	1.02	1.02	7
	6000	1.52	1.52	1.52	1.27	1.27	1.21	1.27	1.27	1.27	7
	6500	1.52	1.52	1.52	1.52	1.27	1.40	1.78	1.52	1.65	7
	7000	2.03	1.78	1.90	2.29	2.29	2.29	2.03	1.78	1.90	7

Table 12

CRACK PROPAGATION FOR BUTT BRAZED GROUP BR2 SPECIMENS

Edge Radius, mm	Cycles	Crack Length, mm Front	Back	Avg	Remarks	Total Cracks Observed
					Specimen 347-1: 347 + NB50	
Distance from bottom, mm				51.80		
1.09	12	Completely separated				1
					Specimen 188-6: HS 188 + CM 52	
Distance from bottom, mm				51.80		
0.86	12	No cracks				
	25	22.86	22.86	22.86	Essentially completely separated	1
					Specimen 316-5: 316 + Nioro	
Distance from bottom, mm				51.80		
0.76	12	No cracks				
	25	21.59	22.61	22.10	Essentially completely separated	1
					Specimen 316-7: 316 + 60 Alloy	
Distance from bottom, mm				51.80		
1.14	12	No cracks				
	25	11.68	12.45	12.06	Specimen removed after 50 cycles	1
	37	12.70	12.70	12.70		1
	50	20.83	20.57	20.70		1

Table 12 (cont.)

Edge Radius, mm	Cycles	Crack Length, mm Front	Back	Avg	Remarks	Total Cracks Observed
					Specimen 316-6: 316 + 60 Alloy	
Distance from bottom, mm				51.80		
1.14	12	No cracks				
	25	6.86	6.35	6.60		1
	37	6.86	7.11	6.98		1
	50	7.11	7.11	7.11		1
	75	21.59	20.32	20.96	Essentially completely separated	1
					Specimen 316-4: 316 + AMI-100	
Distance from bottom, mm				51.80		
0.89	75	No cracks				
	100	4.83	5.59	5.21		1
	150	6.10	6.35	6.22		1
	200	6.60	6.86	6.73		1
	300	6.86	6.86	6.86		1
	400	6.86	6.86	6.86		1
	500	6.86	7.11	6.98		1
					Specimen 800-4: Incoloy 800 + AMI-100	
Distance from bottom, mm				51.80		
1.17	75	No cracks				
	100	5.59	4.57	5.08		1
	150	5.84	5.84	5.84		1
	200	6.35	5.84	6.10		1
	300	6.35	5.84	6.10		1
	400	6.35	6.35	6.35		1
	500	6.86	6.86	6.86		1

Table 12 (cont.)

Edge Radius, mm	Cycles	Crack Length, mm Front	Back	Avg	Remarks	Total Cracks Observed
					Specimen 347-2: 347 + AMI-400	
Distance from bottom, mm				51.80		
1.04	1000	No cracks				
	1500	5.84	5.84	5.84		1
	2000	5.84	5.84	5.84		1
	2500	5.84	5.84	5.84		1
	3000	Completely separated				
					Specimen 800-5: Incoloy 800 + Palniro 1	
Distance from bottom, mm				51.80		
1.18	1000	No cracks				
	1500	6.35	7.11	6.73		1
	2000	6.35	7.11	6.73	Extensive cracking.	1
					Specimen 600-6: Inconel 600 + Palniro 1	
Distance from bottom, mm				51.80		
0.86	1000	No cracks				
	1500	6.60	7.11	6.86		1
	2000	6.60	7.11	6.86	Removed after 2000 cycles	1
					Specimen 600-5: Inconel 600 + Palniro 1	
Distance from bottom, mm				51.80		
1.14	1000	No cracks				
	1500	2.29	2.03	2.16	Specimen inserted after 25 cycles.	1
	2000	2.29	2.03	2.16		1
	2500	20.07	18.54	19.30	Essentially completely separated	1

Table 12 (cont.)

Edge Radius, mm	Cycles	Crack Length, mm Front	Back	Avg	Remarks	Total Cracks Observed
					Specimen X-7: Hastelloy X + NB30	
Distance from bottom, mm				51.80		
0.89	2000	No cracks				
	2500	Completely separated				1
					Specimen X-4: Hastelloy X + Palniro 1	
Distance from bottom, mm				51.80		
0.69	1000	No cracks				
	1500	3.56	4.06	3.81		1
	2000	3.56	4.06	3.81		1
	2500	24.13	24.64	24.38	Essentially completely separated	1
					Specimen X-6: Hastelloy X + 75% AMI-400/25% NB30	
Distance from bottom, mm				51.80		
0.71	3000	No cracks				
	3500	Completely separated				1
					Specimen X-5: Hastelloy X + CM 50	
Distance from bottom, mm				51.80		
0.69	2500	No cracks				
	3000	2.79	2.54	2.66		1
	3500	4.57	3.56	4.06		1
	4000	5.59	5.33	5.46		1
	4500	6.35	5.84	6.10		1
	5000	23.62	24.13	23.82	Essentially completely separated	1
					Specimen 41-6: René 41 + AMI-300	
Distance from bottom, mm				51.80		
1.14	2500	No cracks				
	3000	Completely separated				1

Table 13

CRACK PROPAGATION FOR BRAZED FOIL GROUP BR3

	Crack Length, mm									
	1st Crack			2nd Crack			3rd Crack			Total Cracks
Cycles	Front	Back	Avg	Front	Back	Avg	Front	Back	Avg	Observed
				Specimen X-9 : Hastelloy X + CM 50						
Distance from bottom, mm			25.40							
6500	No cracks									
7000	0.51	0.76	0.76							1
				Specimen 347-3: 347 + NB50						
Distance from bottom, mm			33.27			34.02			47.2	
6500	No cracks									
7000	1.52	2.03	1.78	1.52	1.78	1.65	1.78	1.27	1.53	3

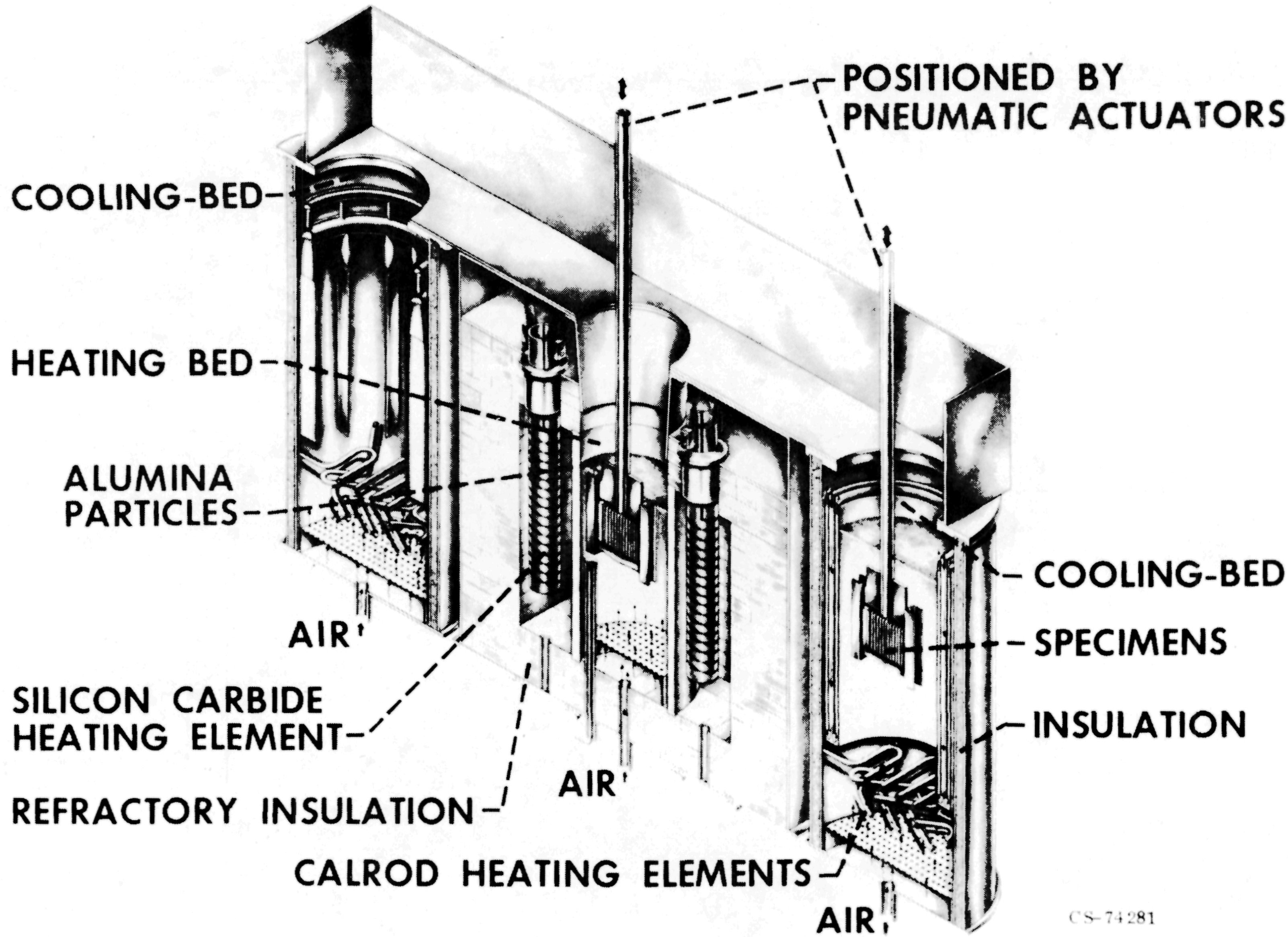
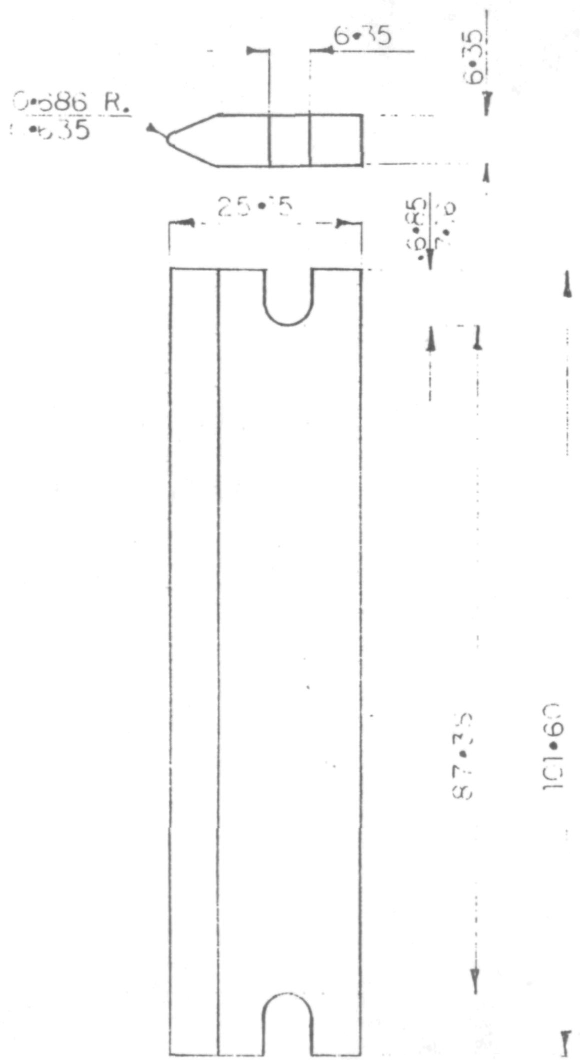
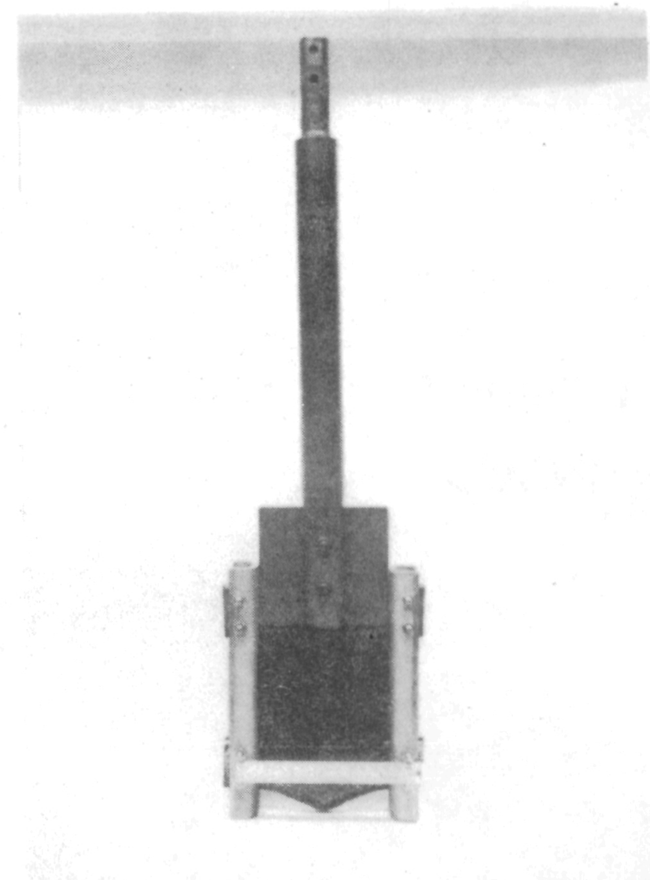


Figure 1
Fluidized Bed Thermal Fatigue Facility



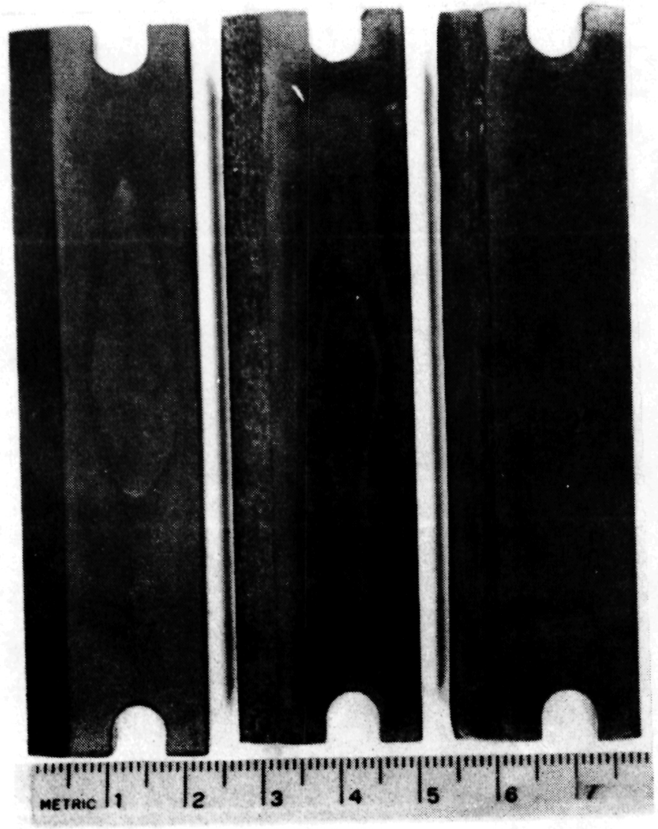
Single-Edge Wedge Specimen
(dimensions in mm)



Neg. No. 45935 1/12X

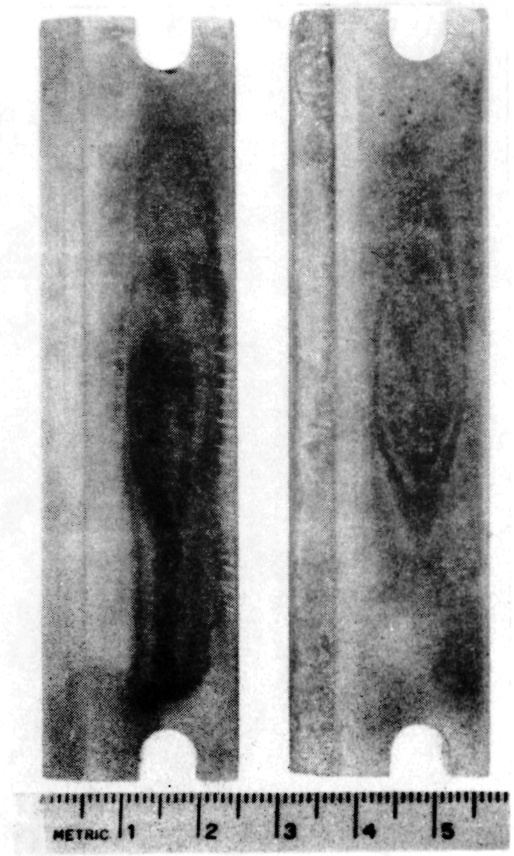
Figure 2

Single-Edge Wedge Test Specimen and Holding Fixture



Neg. No. 43773 1X

316

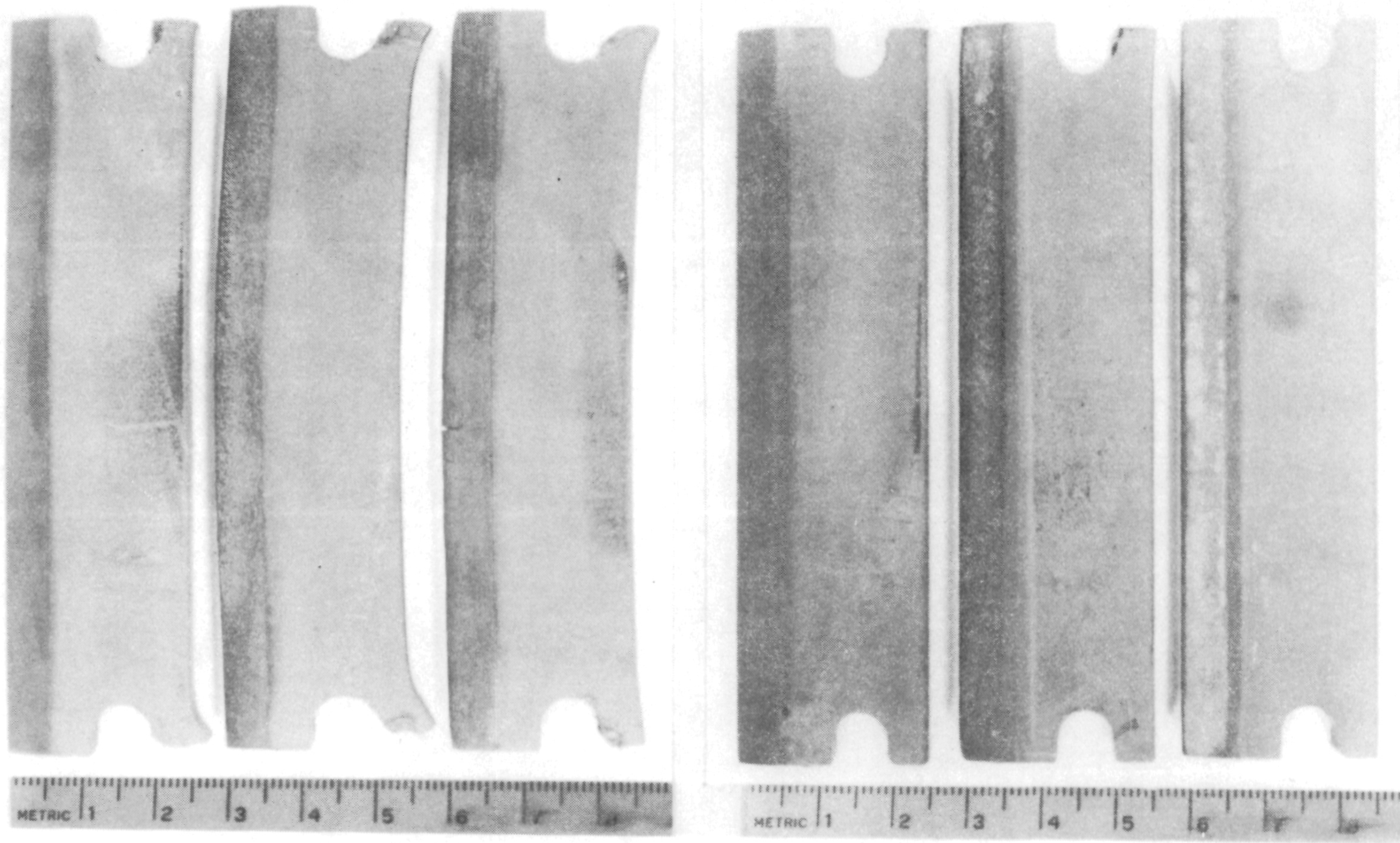


Neg. No. 43775 1X

Hastelloy X

Figure 3

Typical As-Received Appearance of Braze Overlay Group BR1
Single-Edge Wedge Specimens



Neg. No. 44455 1X

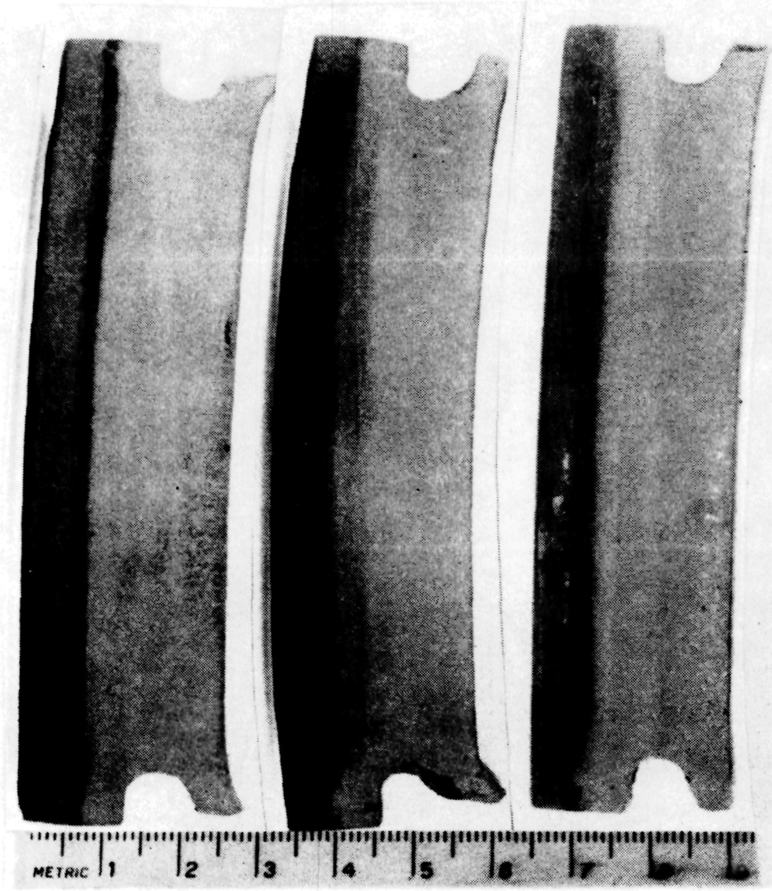
316-1 316-2 316-3

Neg. No. 44450 1X

X-1 X-2 X-3

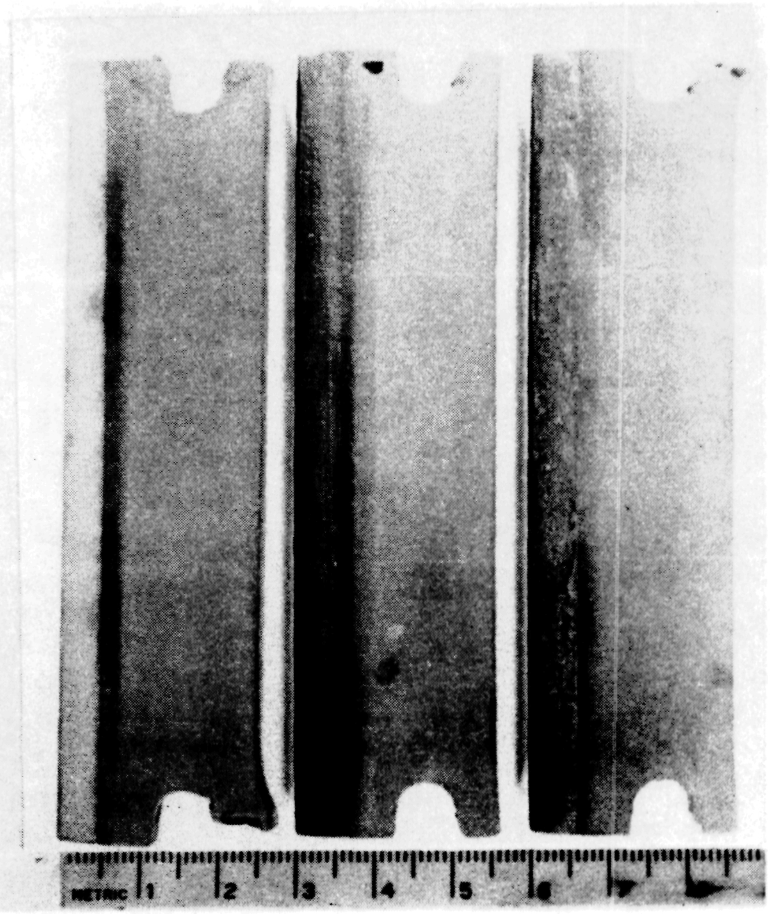
Figure 4

Appearance of 316 and Hastelloy X Group BR1 Specimens after 7000 Thermal Cycles



Neg. No. 44452 1X

800-1 800-2 800-3

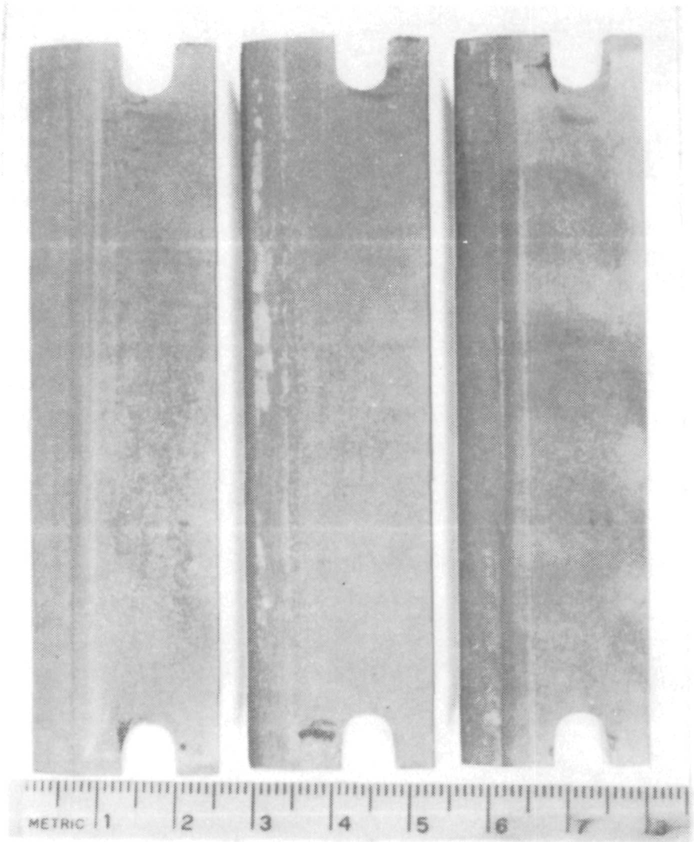


Neg. No. 44451 1X

600-1 600-2 600-3

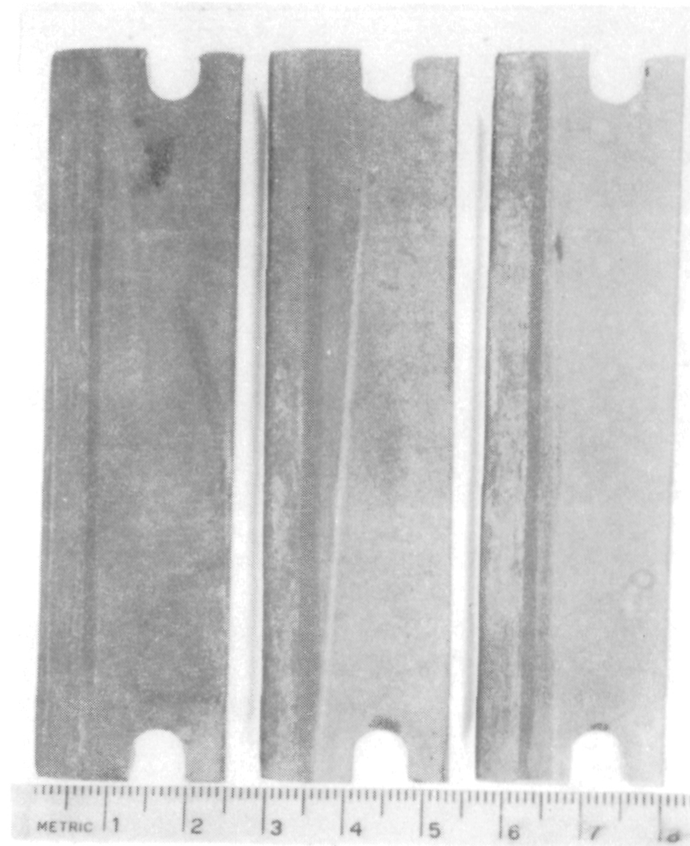
Figure 5

Appearance of Incoloy 800 and Inconel 600 Group BR1 Specimens after 7000 Thermal Cycles



Neg. No. 44453 1X

41-1 41-2 41-3

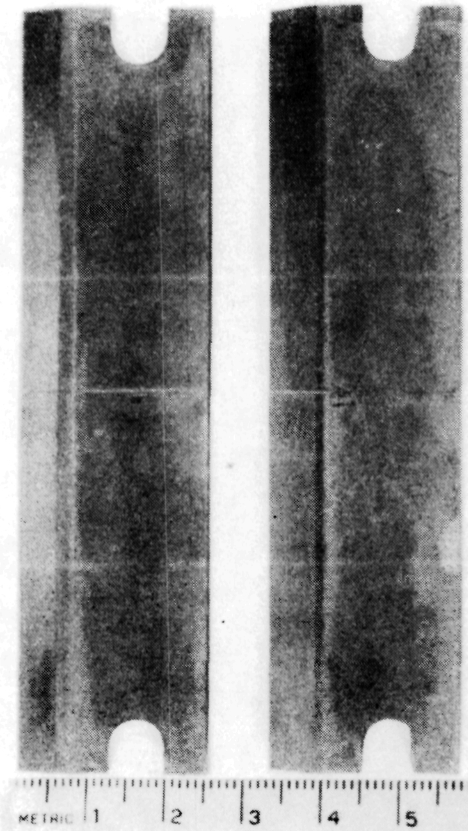


Neg. No. 44454 1X

188-1 188-2 188-3

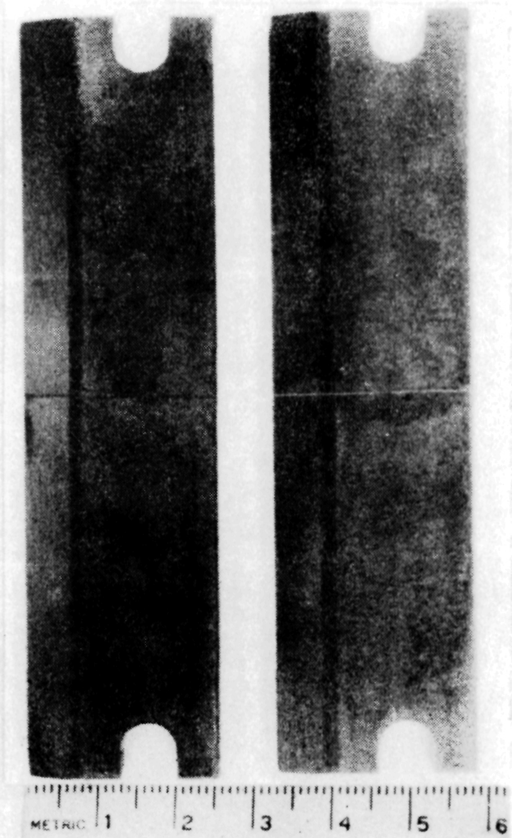
Figure 6

Appearance of René 41 and HS 188 Group BR1 Specimens after 7000 Thermal Cycles



Neg. No. 43762 1X

Inconel 600

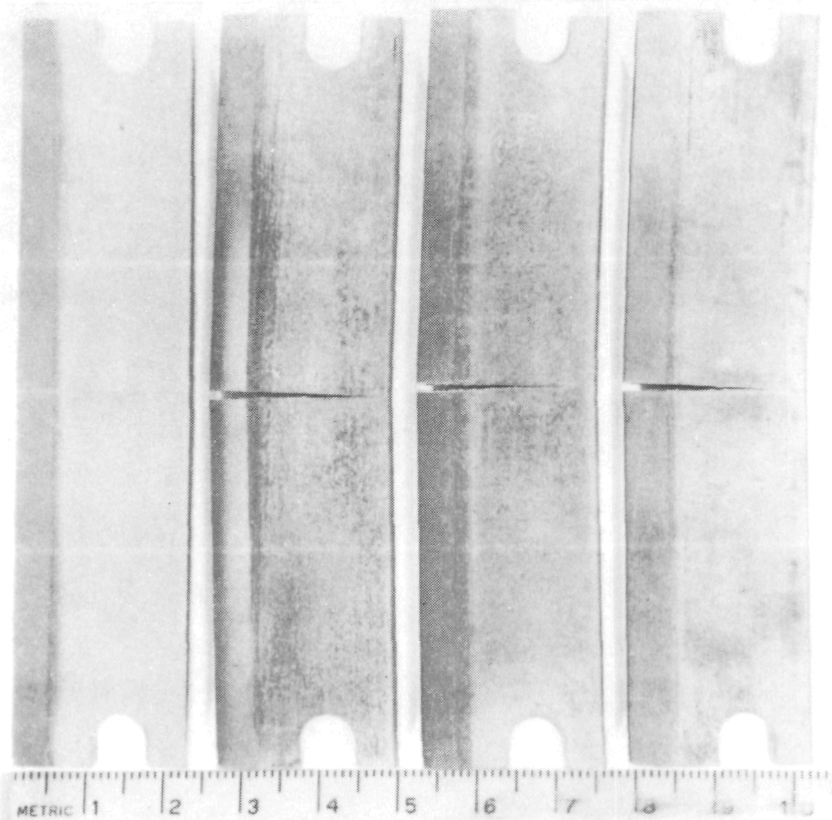


Neg. No. 43764 1X

Hastelloy X

Figure 7

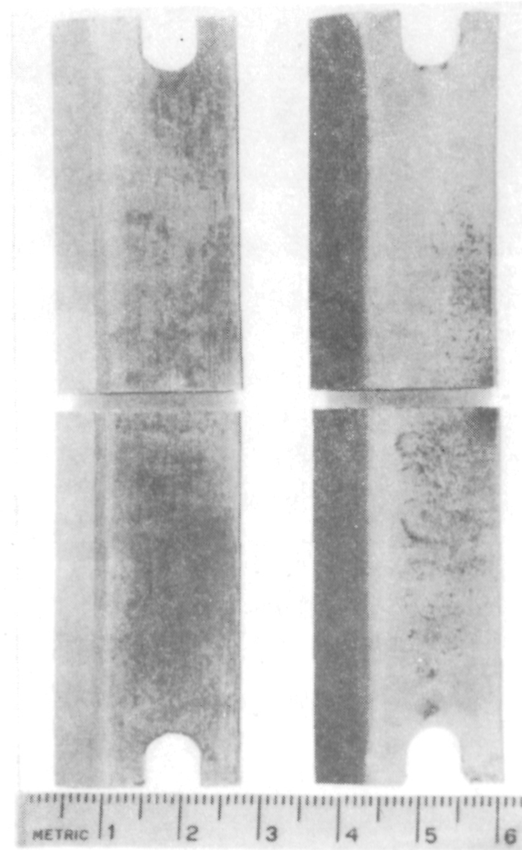
Typical As-Received Surface Appearance of Midspan Butt Brazed Group BR2 Single-Edge Wedge Specimens



Neg. No. 44446 1X

316-4 316-5 316-6 316-7

500 cycles 25 cycles 75 cycles 50 cycles



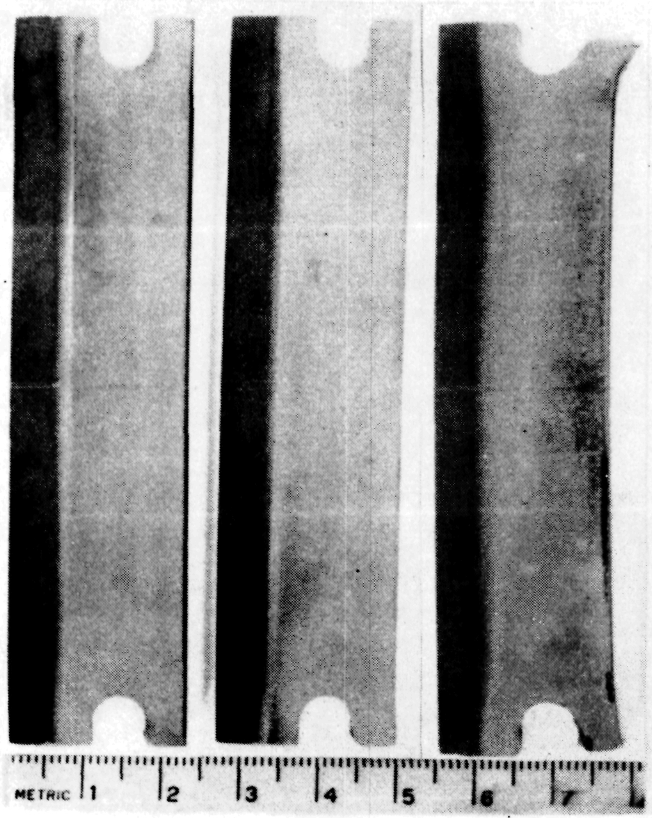
Neg. No. 44458 1X

347-1 347-2

12 cycles 3000 cycles

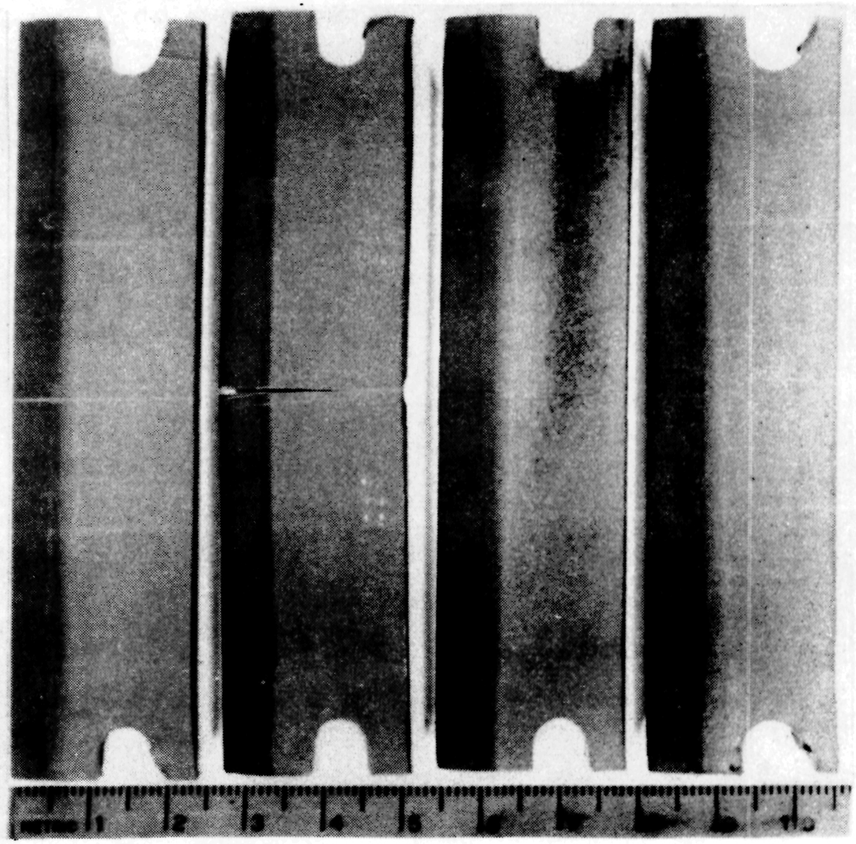
Figure 8

Appearance of 316 and 347 Group BR2 Specimens
after Indicated Thermal Cycles



Neg. No. 44447 1X

800-4 500 cycles | 800-5 2000 cycles | 800-6 11,000 cycles

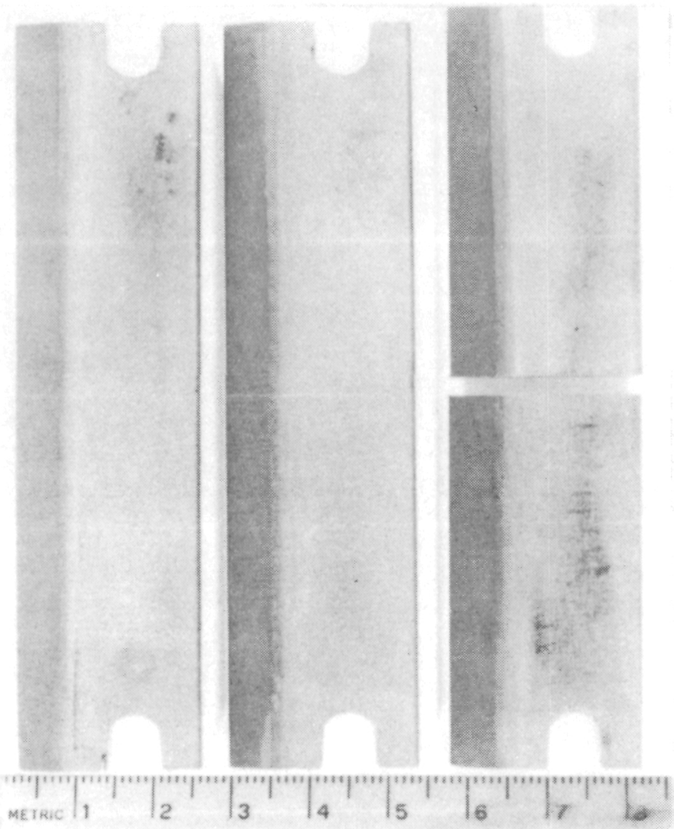


Neg. No. 44448 1X

600-4 11,000 cycles | 600-5 2500 cycles | 600-6 2000 cycles | 600-7 11,000 cycles

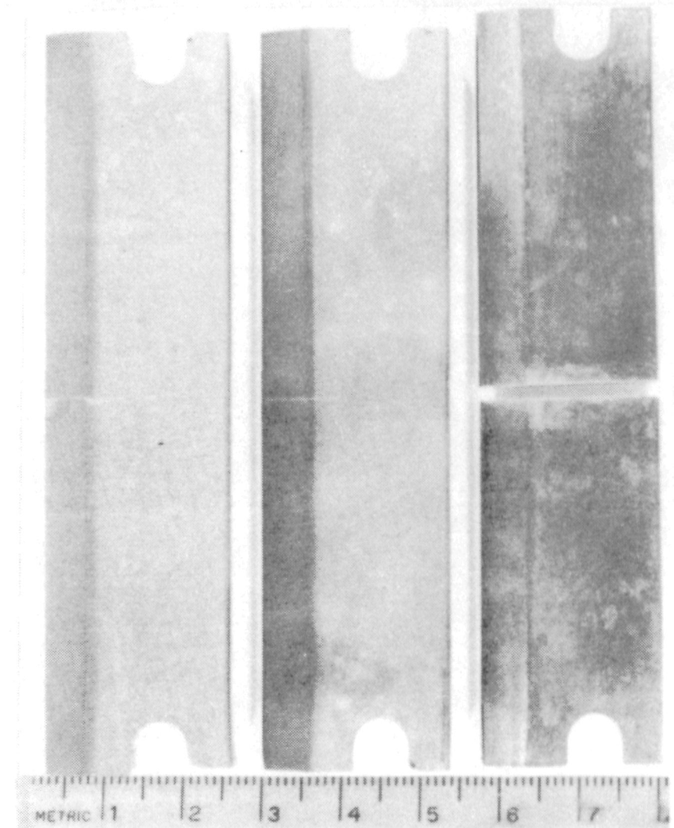
Figure 9

Appearance of Incoloy 800 and Inconel 600 Group BR2 Specimens after Indicated Thermal Cycles



Neg. No. 44457 1X

41-4	41-5	41-6
11,000 cycles	11,000 cycles	3000 cycles

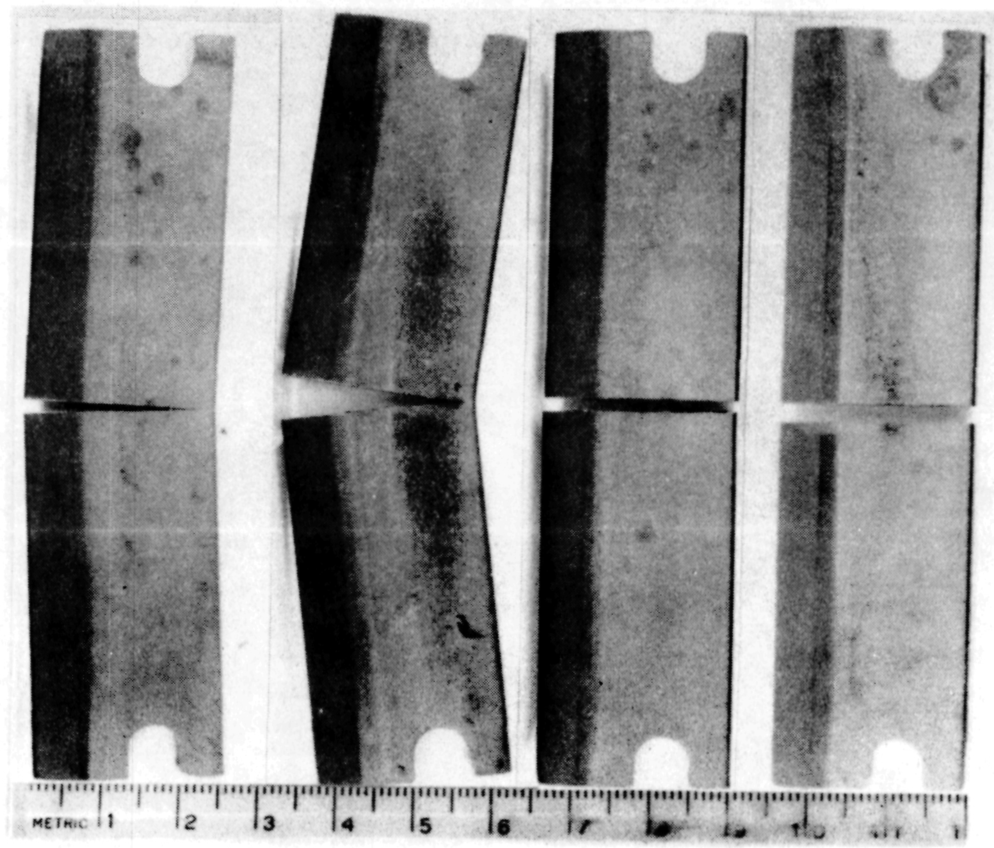


Neg. No. 44456 1X

188-4	188-5	188-6
11,000 cycles	11,000 cycles	25 cycles

Figure 10

Appearance of René 41 and HS 188 Group BR2 Specimens after Indicated Thermal Cycles

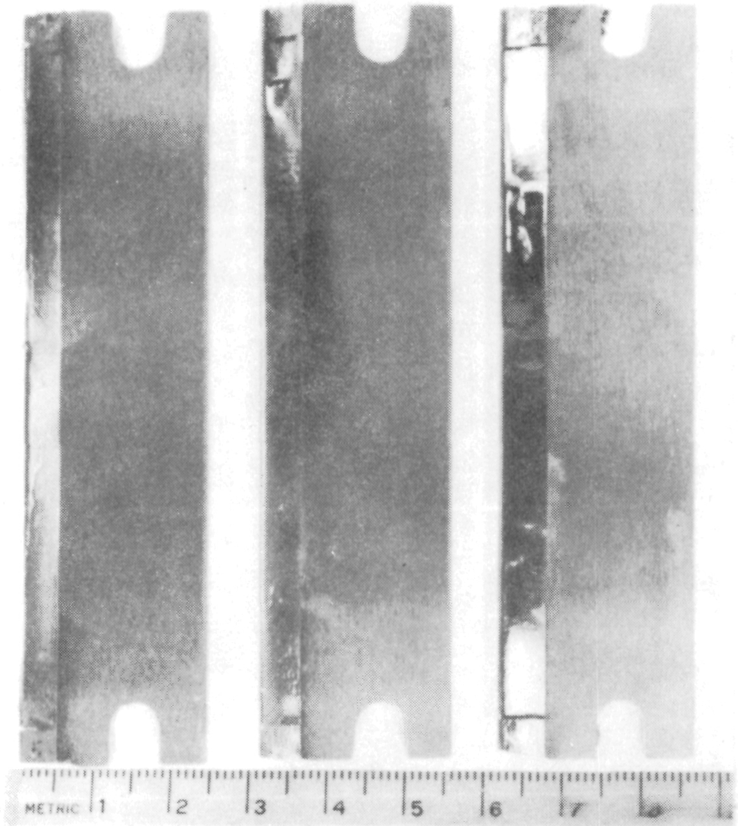


Neg. No. 44449 1X

X-4	X-5	X-6	X-7
2500 cycles	5000 cycles	3500 cycles	2500 cycles

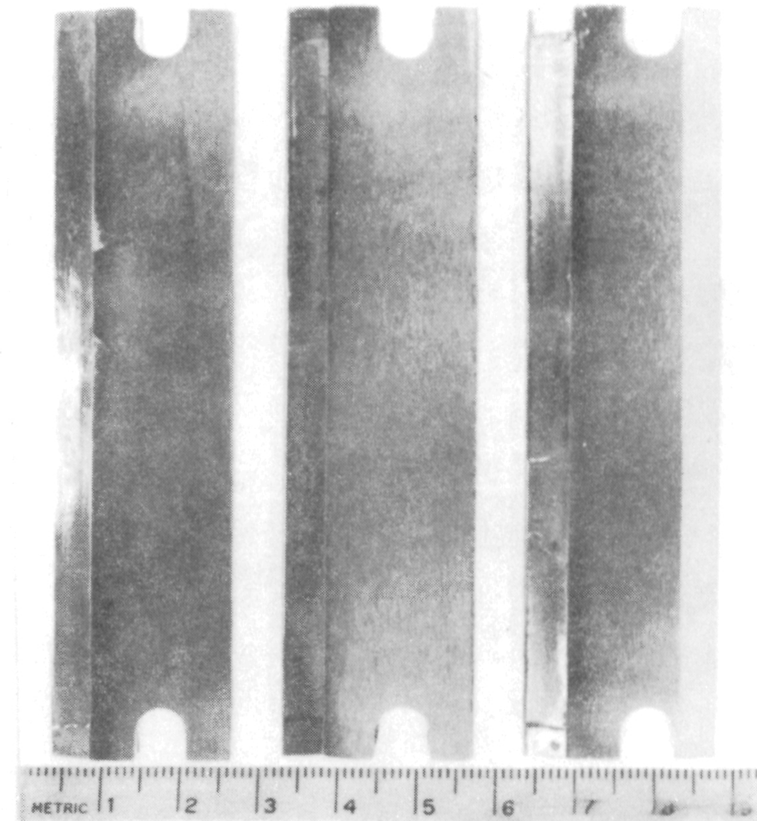
Figure 11

Surface Appearance of Hastelloy X Group BR2 Specimens after Indicated Thermal Cycles



Neg. No. 43939 1X

316

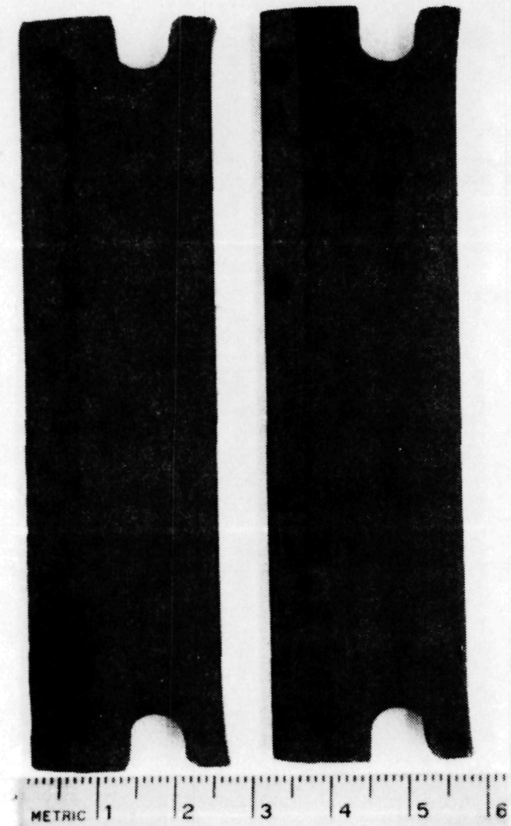


Neg. No. 43936 1X

HS 188

Figure 12

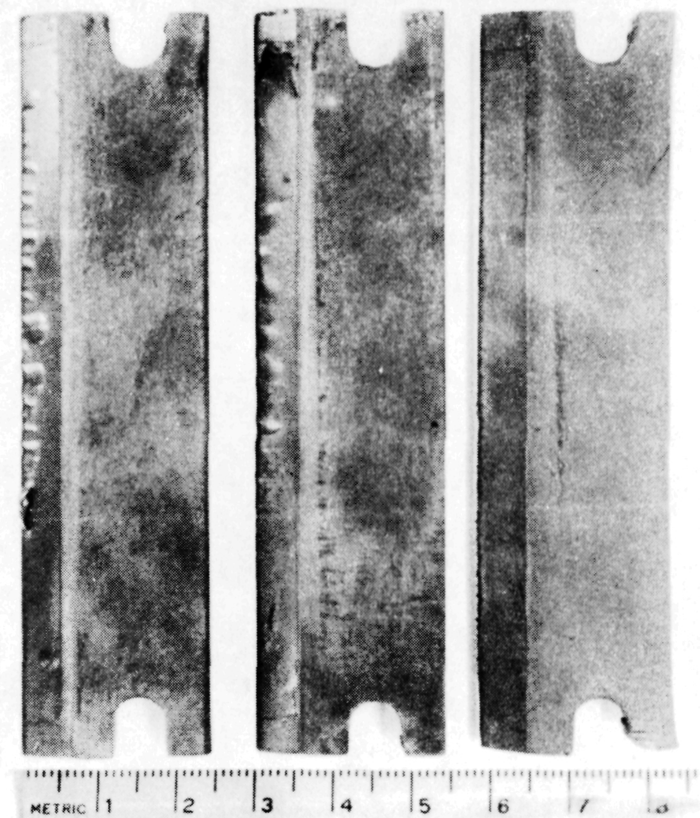
Typical As-Received Surface Appearance of Foil Brazed Group BR3
Single-Edge Wedge Specimens



Neg. No. 45569 1X

347-3 347-4

7000 cycles 7000 cycles



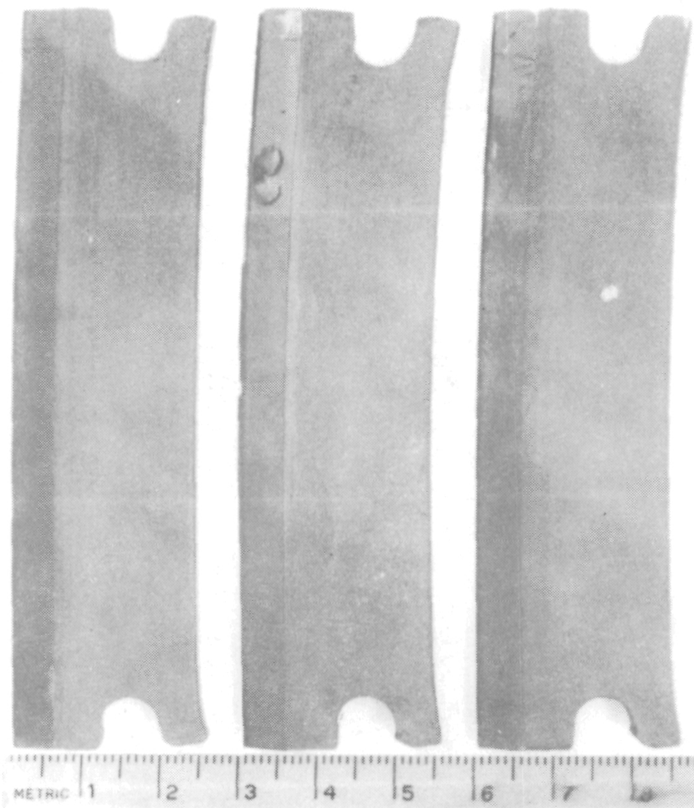
Neg. No. 45572 1X

316-8 316-9 316-10

100 cycles 100 cycles 3000 cycles

Figure 13

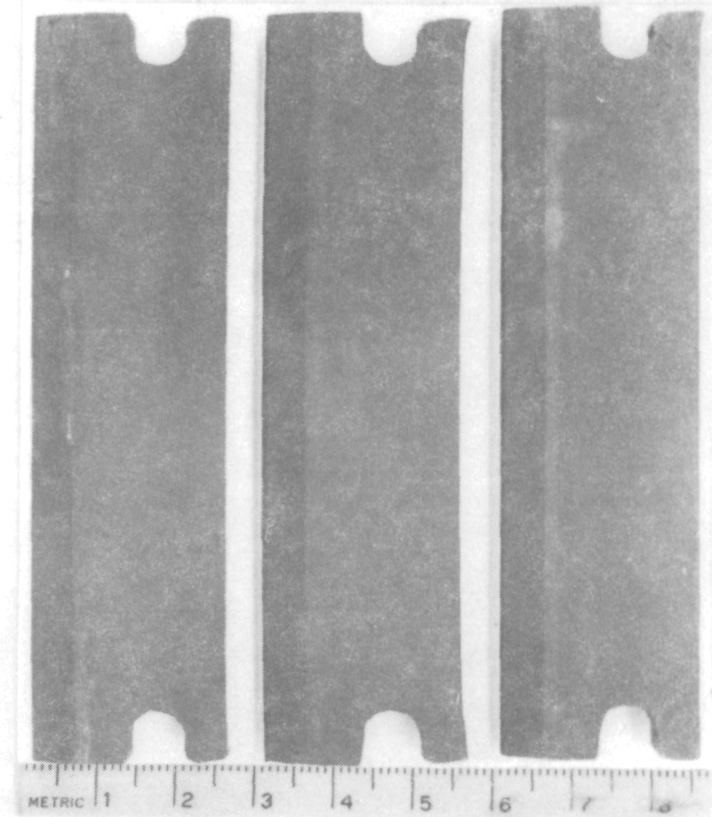
Appearance of 347 and 316 Group BR3 Specimens
after Indicated Thermal Cycles



Neg. No. 45573 1X

800-7 800-8 800-9

7000 cycles 500 cycles 7000 cycles



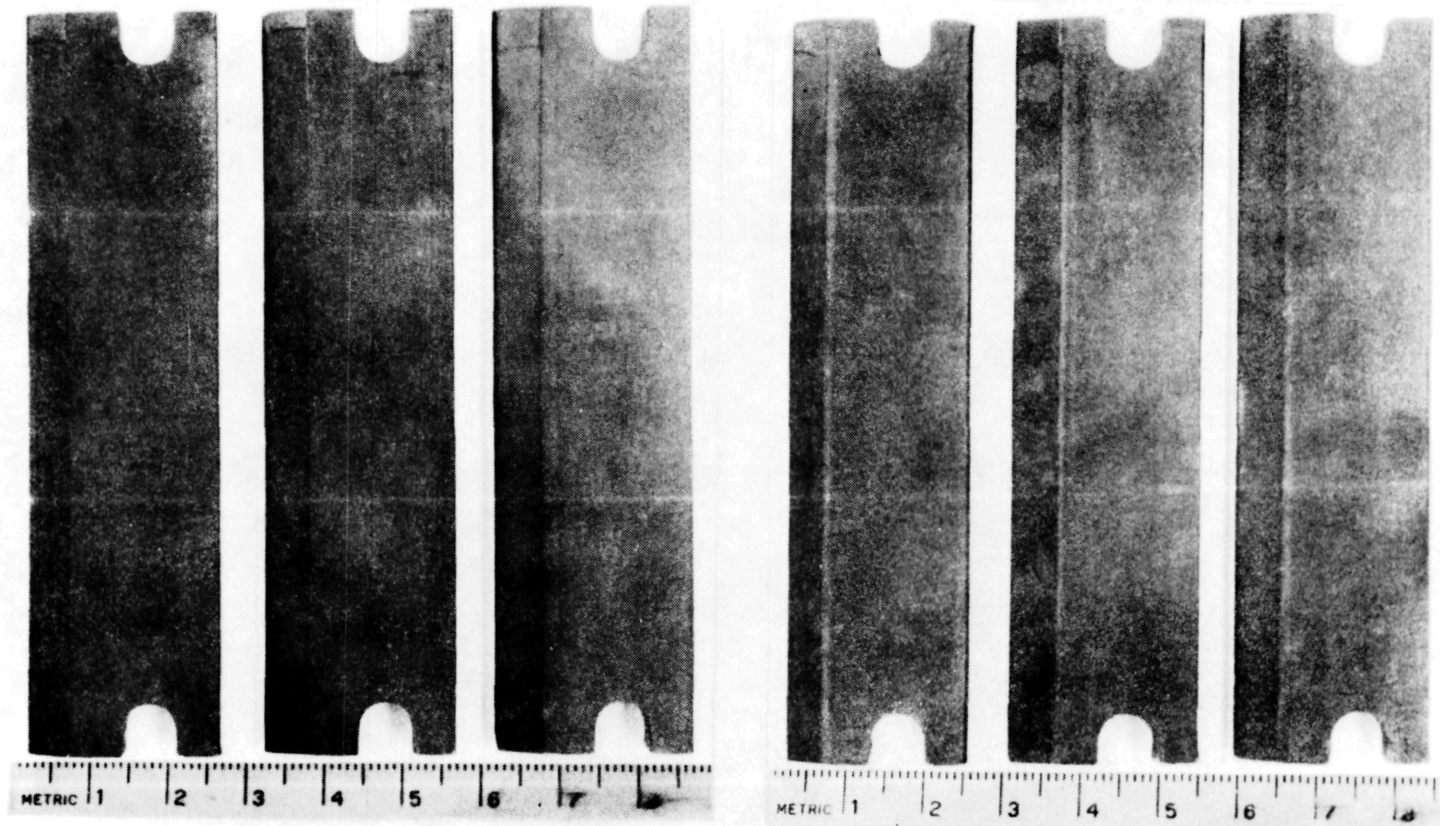
Neg. No. 45574 1X

600-8 600-9 600-10

7000 cycles 7000 cycles 7000 cycles

Figure 14

Appearance of Incoloy 800 and Inconel 600
Group BR3 Specimens after Indicated Thermal Cycles

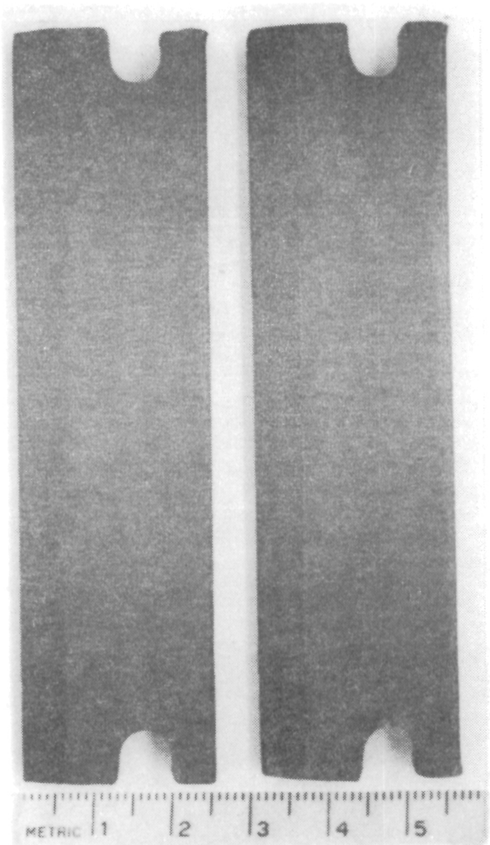


Neg. No. 45570 1X
41-7 41-8 41-9

Neg. No. 45571 1X
188-7 188-8 188-9

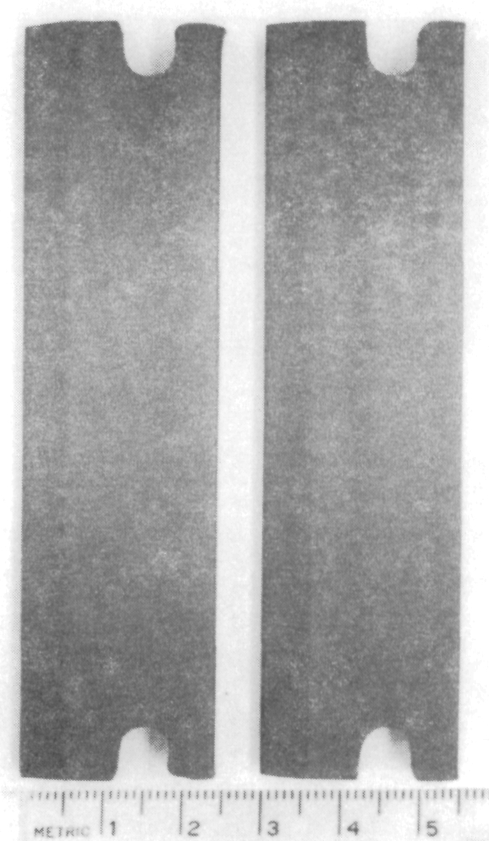
Figure 15

Appearance of René 41 and HS 188 Group BR3 Specimens
after 7000 Thermal Cycles



Neg. No. 45567 1X

X-8 X-9



Neg. No. 45568 1X

X-10 X-11

Figure 16

Surface Appearance of Hastelloy X Group BR3 Specimens after 7000 Thermal Cycles